ANNUAL CONVENTION, DEER PARK, MD.
June 29-July 2, 1915

PROCEEDINGS
OF THE
American Institute
OF
Electrical Engineers

Volume XXXIV
Number 6

JUNE, 1915

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Section I.—Institute Affairs

CONTENTS OF SECTION I.

Section II.—Papers, Discussions and Reports

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COMING MEETINGS

Annual Convention, Deer Park, Md.
June 29th to July 2nd

Panama-Pacific Convention, San Francisco, Cal.
September 16th to 18th

International Engineering Congress, San Francisco, Cal.
September 20th to 25th

PROCEEDINGS
OF THE
American Institute
OF
Electrical Engineers.

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THE EDITING COMMITTEE

GEORGE R. METCALFE, Editor

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Vol. XXXIV June, 1915 No. 6

A. I. E. E. Annual Convention

Arrangements for the 32nd Annual Convention of the American Institute of Electrical Engineers at Deer Park, Md., June 29 to July 2, are practically completed. The Convention Committee and its various sub-committees have been busy during the last two months in preparation for this meeting with the result that a very interesting program is offered in which the technical and entertainment features are nicely balanced. The technical program which follows has been revised and is now complete. The Convention Committee has arranged for the usual entertainment features, and special entertainment for the ladies in attendance will be announced at the time of the convention.

PROGRAM

Reprints of all papers will be available without charge at registration headquarters.

Tuesday, June 29

10.00 A. M. to 12.30 P. M.

President's Address, by P. M. Lincoln.

The Electric Strength of Air—VI, by J. B. Whitehead.

The Reluctance of Some Irregular Magnetic Fields, by John F. H. Douglas.

Irregular Wave Forms, presented by Frederick Bedell.

Part I. *Form Factor and Its Significance*, by Frederick Bedell, assisted by R. Bown and H. A. Pidgeon.

Part II. *Distortion Factors*, by Frederick Bedell, assisted by R. Bown and C. L. Swisher.

Part III. *An Analytical and Graphical Solution for Non-Sinusoidal Alternating Currents*, by F. M. Mizushi.

12.30 to 2.30 P. M.

Sections Committee Luncheon.

2.30 to 3.45 P. M.

Foundations for Transmission Line Towers and Tower Erection—A Symposium.

Part I—J. A. Walls
Part II—J. B. Leeper
Part III—W. E. Mitchell
Part IV—P. M. Downing
Part V—F. C. Connery

3:45 to 5:00 P. M.

Fields of Motor Application (Topical Discussion) by D. B. Rushmore.

Electricity in Grain Elevators, by H. E. Stafford.

9:00 P. M.
Reception.

Wednesday, June 30

10:00 A. M. to 12:30 P. M.

Classification of Alternating-Current Motors, by Val A. Fynn.

The Classification of Electromagnetic Machinery, by Frederick Creedy.

Short Circuits on Alternators, by Comfort A. Adams.

12:30 to 2:30 P. M.

Sections Committee Luncheon.

8:15 P. M.

The Effective Illumination of Streets, by Preston S. Millar.

Systems of Street Illumination, by Charles P. Steinmetz.

Thursday, July 1

10:00 A. M. to 12:30 P. M.

Construction and Maintenance Costs of Overhead Contact Systems. Part I, by E. J. Amberg; Part II, by Ferdinand Zogbaum.

Contact System of the Butte, Anaconda and Pacific Railway, by J. B. Cox.

Third-Rail and Trolley System of the West Jersey and Seashore Railroad, by J. V. B. Duer.

Unprotected Top-Contact Rail for 600-Volt Traction System, by Charles H. Jones.

Contact Conductors and Collectors for Electric Railways, by C. J. Hixson.

Contact System of the Southern Pacific Company—Portland Division, by Paul Lebenbaum.

12:30 to 2:30 P. M.

Board of Directors Luncheon

8:15 P. M.

Conference of Section Delegates and Institute officers.

(All members welcome.)

Friday, July 2

10:00 A. M. to 12:30 P. M.

Phase Angle of Current Transformers, by Chester L. Dawes.

Calibration of Current Transformers by Means of Mutual Inductances, by Charles L. Fortescue.

The Induction Watt-hour Meter, by V. L. Hollister.

The Measurement of Dielectric Losses with the Cathode Ray Tube, by John P. Minton.

12:30 to 2:30 P. M.

Sections Committee Luncheon.

2:30 to 5:00 P. M.

Economic Operation of Electric Ovens, by Percy W. Gumaer.

Class Rates for Electric Light and Power Systems or Territories, by Frank G. Baum.

The official headquarters of the Institute during the convention will be the Deer Park Hotel. The hotel is capable of accommodating 300 people comfortably, and any reasonable number in excess can be accommodated in some of the big cottages grouped about the hotel. In addition to this, Mountain Lake Park and Oakland are near enough to be utilized as overflow quarters if necessary. The hotel contains 36 rooms with private baths, two to four public baths on each floor, and the swimming pools are available to everybody at all times. The rates are on the American plan as follows:

	Per day per person
Single rooms without baths	$4.00
Double rooms " " 2 in room	3.00
" " " " 2 in room	4.00
" " " " 3 in room	4.00
" " " " 4 in room	4.00
" " with " 2 in room	5.00
" " " " 3 in room	5.00
" " " " 4 in room	5.00

Room reservations should be made promptly by letter or wire to Mr. J. H. Murphy, Manager, Deer Park Hotel, 1012 N. W. Superior Avenue, Cleveland, Ohio, for convention dates or longer periods. Deer Park is an ideal place at which to stay over July 4th.

The Baltimore and Ohio Railroad furnishes the following schedule of train service from all important centers to Deer Park, now effective.

FROM EASTERN CITIES.

	55	1	11	3
Lv. New York 23d St.	11.50 p. m.	9.50 a.m.	3.50 p.m.	6.50 p.m.
Lv. New York Liberty St.	1.30 a.m.	10.00 a.m.	4.00 p.m.	7.00 p.m.
Lv. Philadelphia	4.15 a.m.	12.30 p.m.	6.12 p.m.	9.21 p.m.
Lv. Baltimore, Mt. Royal	7.50 a.m.	2.43 p.m.	8.09 p.m.	11.25 p.m.
Lv. Baltimore, Camden	8.00 a.m.	3.00 p.m.	8.00 p.m.	11.38 p.m.
Lv. Washington	9.10 a.m.	4.05 p.m.	9.10 p.m.	12.48 a.m.
Lv. Cumberland	1.35 p.m.	8.20 p.m.	1.05 a.m.	5.03 a.m.
Ar. Deer Park Hotel, Md.	3.16 p.m.	10.04 p.m.	2.50 a.m.	6.46 a.m.

FROM WESTERN CITIES.

		2	4	12
Lv. St. Louis	CT....	9.00 a.m.	1.00 a.m.	10.30 p.m.
Lv. Louisville	"	2.00 p.m.	8.10 a.m.	2.30 a.m.
Lv. Cincinnati	"	6.35 p.m.	12.45 p.m.	8.10 a.m.
Lv. Chillicothe	"	9.30 p.m.	3.43 p.m.	11.08 a.m.
Lv. Parkersburg	ET....	1.15 a.m.	7.25 p.m.	3.05 p.m.
Lv. Grafton	"	4.45 a.m.	11.00 p.m.	6.32 p.m.
Ar. Deer Park Hotel, Md...		6.47 a.m.	1.09 a.m.	8.38 p.m.

	6	8	10	16
Lv. Chicago...............	5.45 p.m.	10.45 a.m.	8.00 a.m.	9.30 p.m.
Lv. Sandusky..............	———	2.30 p.m.	———	———
Lv. Cleveland.............	———	6.00 p.m.	3.35 p.m.	———
Lv. Akron.................	2.50 a.m.	7.20 p.m.	4.55 p.m.	7.25 a.m.
Lv. Pittsburgh............	8.15 a.m.	12.12 a.m.	10.35 p.m.	1.15 p.m.
Ar. Cumberland............	12.40 p.m.	4.35 a.m.	2.55 a.m.	6.00 p.m.
Lv. Cumberland...........	1.35 p.m.	5.03 a.m.	5.03 a.m.	8.20 p.m.
Ar. Deer Park Hotel, Md...	3.16 p.m.	6.46 a.m.	6.46 a.m.	10.04 p.m.

	2
Lv. Columbus.............	7.30 p.m.
Lv. Wheeling..............	12.45 a.m.
Ar. Deer Park Hotel, Md...	6.47 a.m.

Trains 55, 1 and 3 have through Pullman cars from New York, Philadelphia, Baltimore and Washington to Deer Park Hotel.

Train No. 11 has through Pullman car from Baltimore to Deer Park Hotel, but connects at Washington with the " Royal Limited " from New York and Philadelphia.

Trains Nos. 2 and 12 have through sleeping cars from St. Louis and Cincinnati to Deer Park Hotel, and Train No. 2 has through sleeping car from Louisville to Deer Park Hotel. Train No. 4 has through sleeping cars from Cincinnati to Deer Park Hotel.

Trains Nos. 8, 6, 10 and 16, from Chicago and Pittsburgh, make connections at Cumberland with trains to Deer Park Hotel as per schedule, change of cars at Cumberland being necessary.

Train No. 2 has through sleeping car from Columbus and Wheeling to Deer Park Hotel.

	RAILROAD FARES		PULLMAN FARES	
	One-Way	Round-trip	Lower Berth	Drawing-Room
New York.................	$11.09	$17.00	$2.50	$9.00
Philadelphia..............	8.84	13.00	2.25	8.00
Baltimore.................	6.44	9.00	1.50	6.00
Washington...............	6.01	8.00	1.50	6.00
Pittsburgh................	*5.43	7.95	2.00	7.00
Pittsburgh................	†5.70			
Cincinnati................	9.83	12.75	2.00	7.00
St. Louis.................	19.90	27.15	4.00	14.00
Chicago..................	14.69	22.80	3.50	13.00
Buffalo...................	10.12	17.35	No through	Pullman service
Cleveland.................	7.29	11.70	" "	" "
Detroit...................	11.07	17.55	" "	" "

*—Via Cumberland.

†—Via Connellsville or Wheeling.

NOTE: From Atlanta, the Southern Railway round trip rate to Deer Park is $30.25. Southern Railway train No. 38 leaves Atlanta 12:05 p. m., arriving at Washington 7:45 a.m.; train No. 30 leaves Atlanta 2:25 p. m., arriving at Washington 10:40 a. m. See table above for connections from Washington to Deer Park.

Panama-Pacific Convention

The arrangements for the Panama Pacific Convention which is to be held on September 16th to 18th, the week previous to the International Engineering Congress, are being actively developed at the hands of the general Convention Committee and of the Meetings and Papers Committee of the Institute. The technical sessions will be held in the morning and afternoon of September 16th and 17th, and the number of papers already in sight will probably necessitate holding parallel sessions on both of these days. A number of papers has already been accepted for this meeting and it is expected that a tentative program will be published in the July issue of the PROCEEDINGS.

Transportation to Panama-Pacific Convention and International Engineering Conress

Members of the Institute in the eastern part of the country who expect to attend the Panama-Pacific Convention of the Institute, September 16-18, and the International Engineering Congress, September 20-25, in San Francisco, are reminded that if they desire to take advantage of the special transportation arrangements that have been made by the Congress authorities, prompt application should be made for reservations on the special train which will be provided for the members of the Institute and the other societies interested.

Complete information regarding this special train was given in the circular mailed to the entire membership of the Institute under date of March 22. The train will leave New York, Grand Central Terminal, at 7:45 p.m., Thursday, September 9, and will arrive in San Francisco on Wednesday evening, September 15. Applications for reservations should be made to Mr. G. S. Harner, Passenger Agent, New York Central Lines, 1216 Broadway, New York.

A special arrangement has also been made for reservations on the Sunset Limited, over the Southern Pacific Lines, from New Orleans to San Francisco, for the benefit of members who cannot join the party from New York. This train will leave New Orleans on Sunday, September 12 at 11:00 a.m., and will arrive in San Francisco on Wednesday, September 15, at 1:00 p.m. Reservations for this trip may be made by addressing Mr. J. H. R. Parsons, General Passenger Agent, Southern Pacific Company, New Orleans, La. In asking for reservations the statement should be made that the request is in connection with the engineering party.

Numerous tours and excursions to California are being arranged by various tourists agencies and by individuals, and circulars describing some of these tours and containing references to the engineering meetings to be held in San Francisco are being mailed to many Institute members, some of whom have erroneously assumed that at least one of these circulars emanated from, or was authorized by, the engineering societies interested. Members are therefore rqeuested to note particularly that the only official transportation arrangements, from the East to San Francisco, for Institute members and for the members of the other societies participating in the International Engineering Congress, are those referred to above and which are covered in detail in the circular of March 22 issued by the Transportation Committee of the Congress.

Proposed Reserve Corps of Engineers

Early in the present year there was an informal conference held in New York at which the establishment of a volunteer reserve corps of engineers for the United States Army, representing all branches of the engineering profession, was discussed. The following five national engineering societies were rep-

resented: American Institute of Consulting Engineers, American Society of Mechanical Engineers, American Institute of Mining Engineers, American Society of Civil Engineers, American Institute of Electrical Engineers.

The matter was considered at the meeting of the Board of Directors of the Institute held February 19 and resolutions were adopted at that time to the effect that the Board was in hearty sympathy with the proposed movement, and with a view to giving enthusiastic support and cooperation in any plan or method of procedure proposed by the War Department, the President was authorized to appoint a committee to represent the Institute in connection therewith.

In accordance with this action, President Lincoln has appointed the following committee: Messrs. Bion J. Arnold, Chairman, Chicago, Ill., John Harisberger, Seattle, Wash., Ralph D. Mershon, New York, N. Y., A. M. Schoen, Atlanta, Ga., and Charles W. Stone, Schenectady, N. Y.

The other national engineering societies named above have also appointed committees to represent them. These various committees will, it is understood, form a joint committee representing the entire engineering profession, to cooperate with the War Department, which is now giving careful study to the matter with a view to formulating a comprehensive plan of a permanent nature, whereby the services of the members of the profession, who so desire, will be available, if needed.

Annual Meeting of the Institute, New York, May 18, 1915

The Annual Meeting of the Institute (309th meeting) was held in the evening of May 18, 1915, in the auditorium of the Engineering Societies Building, New York.

President P. M. Lincoln called the meeting to order at 8:20 p.m., and asked Secretary Hutchinson to present the report of the Board of Directors for the fiscal year ending April 30, 1915. Printed copies of the report, which appears in Section II of this issue, had been distributed at the meeting.

President Lincoln then asked Mr. Hutchinson to read the report of the Committee of Tellers on Election of Officers. (This report is printed elsewhere in Section I). The president thereupon announced the election of the following officers, to assume office at the beginning of the administrative year, August 1, 1915: President, Mr. John J. Carty, New York; Vice-Presidents, Messrs. Comfort A. Adams, Cambridge, Mass., J. Franklin Stevens, Philadelphia, Pa., and William McClellan, New York; Managers, Messrs. Harold Pender, Philadelphia, Pa., C. E. Skinner, Pittsburgh, Pa., John B. Taylor, Schenectady, N. Y., and F. B. Jewett, New York; Treasurer, Mr. George A. Hamilton, Elizabeth, N. J.

President Lincoln introduced the president-elect, Mr. John J. Carty, chief engineer of the American Telephone and Telegraph Company. Mr. Carty spoke briefly, expressing his gratitude for the honor conferred upon him by the Institute in electing him president, twenty-eighth in a line which included the guest of the evening, Dr. Bell. President-elect Carty also voiced his appreciation of the courtesy of President Lincoln in delegating to him, as a representative of telephone engineers, the privilege of presenting the Edison Medal to the inventor of the telephone.

The annual business meeting of the Institute was followed by the presentation of the Edison Medal to Dr. Alexander Graham Bell.

Presentation of the Edison Medal to Dr. Alexander Graham Bell

At the conclusion of the annual business meeting of the Institute in the auditorium of the Engineering Societies Building, New York, on May 18, 1915, occurred the ceremony of presentation

of the Edison Medal to Dr. Alexander Graham Bell, the inventor of the telephone. The presentation was witnessed by a large audience of members of the Institute, telephone engineers, and ladies. One of the enjoyable features of the occasion was the music by the Blue Bell Orchestra of the New York Telephone Society.

President Lincoln, called upon Dr. Schuyler Skaats Wheeler, chairman of the Edison Medal Committee, to preside. Dr. Wheeler gave a brief account of the establishing of the Edison Medal, by associates of Mr. Thomas A. Edison, in commemoration of his invention of the incandescent electric light. The Edison Medal was designed by James Earle Frazer, and bears on its obverse a portrait of Mr. Edison and on its reverse an allegorical conception, " The Genius of Electricity Crowned by Fame." Since the first award in 1909 to Elihu Thomson, Frank J. Sprague, George Westinghouse, William Stanley and Charles F. Brush have been thus honored, and Alexander Graham Bell is the sixth recipient of the Edison Medal.

Dr. Wheeler then introduced the speaker of the evening, Mr. Thomas A. Watson, of East Braintree, Mass., who was the mechanical expert assisting Professor Bell in his experiments which led to the invention and practical working out of the telephone, who constructed the telephone receiver through which he heard Professor Bell's voice on June 3, 1875, and who was afterwards founder and president of the Fore River Ship Building Company. Mr. Watson was elected a Fellow of the A. I. E. E. by the Board of Directors on the day of the Annual Meeting. Mr. Watson's exceedingly interesting address, which told the complete story of the invention of the telephone, will be printed in full in a coming issue of the PROCEEDINGS.

President-elect J. J. Carty, acting for the President, and pursuant to the decision of the Edison Medal Committee of the Institute, then presented the Edison Medal to Past-President Alexander Graham Bell, addressing him in these words:

" Of all the men who ever lived, it remained for you to found the art of transmitting speech electrically. You revealed to mankind the method of electrically transmitting the tones of the human voice to distant places. You were the first to provide the apparatus to do this marvel. You were the first to speak through the electric speaking telephone, and your voice was the first to be heard in the telephone receiver. As long as men can speak, your name will be spoken with honor and with praise, and as long as men can hear they will listen with admiration and with gratitude to the story of your immortal achievement."

Dr. Bell, in his words of acceptance, spoke in an inspiring tone of prophecy of the vast fields still unexplored in the physical universe, awaiting the inventive and constructive daring of the electrical engineers of the future.

Organization Meeting of the Engineering Foundation

The Engineering Foundation, the first public announcement of which was made at a meeting in the Engineering Societies Building on January 27, 1915, reported in the February PROCEEDINGS, held its first regular meeting on May 25. At this meeting Rules of Administration were adopted and the following officers were elected: chairman, Gano Dunn; vice-chairman, Edward D. Adams; secretary, F. R. Hutton; treasurer, Joseph Struthers.

This is a professional engineering trust organized along the lines of the Cleveland, Carnegie, Rockefeller and Sage Foundations, by the United Engineering Society, representing jointly the national organizations of electrical, mining and mechanical engineers, with the co-operation of the national organization of civil engineers, combining about 30,000 members.

The Engineering Foundation was made possible through the generosity

of a distinguished engineer, Ambrose Swasey, of Cleveland, who made the initial gift of a quarter of a million dollars to be devoted to the benefit of mankind through fostering engineering research. The Board administering this trust consists of Mr. Edward D. Adams, banker; Mr. Gano Dunn, president of the J. G. White Engineering Corporation; Mr. Howard Elliott, president New York, New Haven and Hartford Railroad; Dr. Alexander C. Humphreys, president of Stevens Institute of Technology; Dr. Charles Warren Hunt, secretary American Society of Civil Engineers; Dr. A. R. Ledoux, past-president American Institute of Mining Engineers; Dr. M. I. Pupin, professor of electromechanics, Columbia University; Mr. Charles E. Scribner, chief engineer Western Electric Company; Mr. J. Waldo Smith, chief engineer, Board of Water Supply, Gas and Electricity, City of New York; Mr. Jesse M. Smith, past-president, American Society of Mechanical Engineers, and Mr. Benjamin B. Thayer, president Anaconda Copper Company.

The Board telegraphed Mr. Swasey greetings and appreciation of his generosity and pledged itself to carrying out his cherished aims.

Applications for the use of funds were received in large numbers and a committee was appointed to consider them, consisting of Dr. A. R. Ledoux, chairman; Mr. J. Waldo Smith, Dr. M. I. Pupin, and Dr. Alexander C. Humphreys. Most of the applications were in such form that they could not be considered and the committee is preparing a schedule of requirements with which applications will have to comply.

The Engineering Foundation is the first of its kind devoted to engineering interests.

Classification of Technical Literature

Delegates from about twenty national technical and scientific societies met in the Engineering Societies Building, 29 West 39th Street, New York City, on May 21, 1915, to perfect a permanent organization, the purpose being to prepare a classification of the literature of applied science which might be generally accepted and adopted by these and other organizations.

There was a generally expressed opinion that such a classification, if properly prepared, might well serve as a basis for the filing of clippings, for cards in a card index, and for printed indexes; and that the publishers of technical periodicals might be induced to print against each important article the symbol of the appropriate class in this system, so that by clipping these articles a file might be easily made which would combine in one system these clippings, together with trade catalogues, maps, drawings, blue prints, photographs, pamphlets and letters classified by the same system.

By request, Mr. W. P. Cutter, the Librarian of the Engineering Societies' Library, and a delegate from the American Institute of Mining Engineers, read a paper on "The Classification of Applied Science," in which, after describing the existing classifications, of one of which he is the author, stated that, in his opinion, no one of these, although having excellent features, was complete and satisfactory enough to be worthy of general adoption. He outlined a plan whereby a central office could collate all the existing classifications, and, with the help of specialists in the various national societies interested, might compile a general system, which, although perhaps not absolutely perfect, might meet with general acceptance and adoption.

Permanent organization was effected by the election of the following officers: chairman, Fred R. Low; secretary, W. P. Cutter; executive committee, the above, with Edgar Marburg, H. W. Peck and Samuel Sheldon.

It was agreed that a special invitation to participate by the appointment of a delegate be sent to other national

societies which might be interested in the general plan.

The following societies were represented by delegates: Samuel Sheldon, Library Board, United Engineering Society and American Institute of Electrical Engineers; Richard Moldenke, American Foundrymen's Association; C. Clifford Kuh, Society for Electrical Development; Cullen W. Parmelee, American Ceramic Society; Sullivan W. Jones, J. A. F. Cardiff, American Institute of Architects; Geo. F. Weston, American Society of Agricultural Engineers; F. L. Pryor, American Society of Refrigerating Engineers; H. W. Peck, American Gas Institute; Nicholas Hill, American Water Works Association; Edwin J. Prindle, L. P. Alford, L. P. Breckenridge, American Society of Mechanical Engineers; F. J. T. Stewart, National Fire Protection Association; J. J. Blackmore, American Society of Heating and Ventilating Engineers; C. F. Clarkson, Society of Automobile Engineers; F. L. Bishop, Society for the Promotion of Engineering Education; George R. Olshausen, U. S. Bureau of Standards; E. C. Crittenden, American Physical Society; Alfred Rigling, Franklin Institute; W. P. Cutter, American Institute of Mining Engineers; Edgar Marburg, American Society for Testing Materials; A. S. McAllister, National Electric Light Association, American Electrochemical Society and Illuminating Engineering Society; C. E. Lindsay, American Railway Engineering Association; G. W. Lee, Librarian.

The Executive Committee was charged with the task of enlarging the membership of the committee to include delegates from all similar national organizations, and the preparation of a plan for further action.

The delegates present expressed most hearty and enthusiastic personal interest in any system which might be worthy of general adoption; they could not, of course, at this early date, promise anything more than moral support of the idea, reserving for themselves and for their societies the right to examine thoroughly any system that might be evolved, before recommending its adoption.

The name adopted for this organization is "Joint Committee on Classification of Technical Literature," and the address of the Secretary, Mr. W. P. Cutter, is 29 West 39th Street, New York City.

Directors' Meeting, New York, May 18, 1915

The regular monthly meeting of the Board of Directors of the Institute was held in New York on Tuesday, May 18, at 3:00 p.m.

There were present: President P. M. Lincoln, Pittsburgh, Pa.; Past-President Ralph D. Mershon, New York; Vice-Presidents C. E. Scribner, New York, and Farley Osgood, Newark, N. J.; Managers C. A. Adams, Cambridge, Mass., J. Franklin Stevens, Philadelphia, Pa., B. A. Behrend, Boston, Mass., L. T. Robinson, Schenectady, N. Y., William McClellan, Bancroft Gherardi and A. S. McAllister, New York, John H. Finney, Washington, D. C.; Treasurer George A. Hamilton, Elizabeth, N. J., and Secretary F. L. Hutchinson, New York.

The action of the Finance Committee in approving monthly bills amounting to $9,345.59 was ratified.

The annual reports of the Finance Committee, and of the Treasurer, for the year ending April 30, 1915, were presented and accepted.

Upon the recommendation of the Board of Examiners, the Board of Directors elected one applicant as a Fellow, six as Members, and 46 as Associates, transferred one Associate to the grade of Member, and ordered the enrolment of 42 students, in accordance with the lists printed in this issue of the PROCEEDINGS.

Upon the petition of 28 Institute members in Denver, Colo., and with the approval of the Sections Committee, authority was granted for the organization of a Section in Denver.

The Annual Report of the Board of Directors for the fiscal year ending April 30, 1915, which had been prepared by the Secretary, containing a summary of the Institute's activities during the year, together with statements showing the condition of the Institute's finances, was approved for presentation to the membership at the Annual Meeting of the Institute in the evening. Copies of this report were distributed at the Annual Meeting, and the report is published in Section II of this issue of the PROCEEDINGS.

The annual reports of committees for the same period, abstracts of which had been incorporated in the directors' annual report, were presented and accepted.

A considerable amount of other business was transacted by the Board, reference to which will be found under appropriate headings in this and future issues of the PROCEEDINGS.

Report of Committee of Tellers on Election of Officers

To the President,
American Institute of Electrical Engineers.

DEAR SIR:—This committee has carefully canvassed the ballots cast for officers for the year 1915-1916. The result is as follows:

Total number of ballot envelopes received		2368
Rejected on account of bearing no identifying name on outer envelope, according to Article VI, Section 33 of the Constitution	24	
Rejected on account of voter being in arrears for dues on May 1, 1915, as provided in the Constitution and By-Laws	38	
Rejected on account of ballot not being enclosed in inner envelope, or on account of inner envelope bearing an identifying name, according to Article VI, Section 33 of the Constitution	37	
Rejected on account of having reached the Secretary's office after May 1, according to Article VI, Section 33 of the Constitution	24	123
Leaving as valid ballots		2245

These 2245 valid ballots were counted and the result is shown as follows:

For President	
John J. Carty	2244
Scattering and blank	1
	2245
For Vice-Presidents	
Comfort A. Adams	2178
J. Franklin Stevens	2104
William McClellan	1953
*Harris J. Ryan	352
Scattering and blank	148
	6735
For Managers	
Harold Pender	2203
C. E. Skinner	2191
John B. Taylor	2183
F. B. Jewett	1973
Henry Floy	111
N. J. Neall	87
Scattering and blank	232
	8980
For Treasurer	
George A. Hamilton	2243
Scattering and blank	2
	2245

Respectfully submitted,
FREDERICK BORCH, *chairman.*
CHAS. A. ROHR.
W. S. HOYT.
R. C. DARROW.
Committee of Tellers.

May 7, 1915.

*As announced in the April PROCEEDINGS and elsewhere, Professor Ryan was appointed in March, by the Board of Directors of the Institute, to the office of Honorary Vice-President, taking effect immediately. This office was created in order that the Institute might be represented on the Pacific Coast during the Panama-Pacific Exposition by a special officer of high rank.

Past Section Meetings

Baltimore.—April 10, 1915, U. S. Naval Academy, Annapolis, Md. Visit to United States Experimental Station and Electrical Laboratories. Baseball game between Naval Cadets and Colgate University. Attendance 18.

Boston.—April 23, 1915, Chipman Hall, Tremont Temple. Illustrated address by Mr. Frank Hodgdon on "Construction and Apparatus of the

Commonwealth Pier No. 5, with Special Reference to the Application of Electricity." Joint meeting of the Civil, Mechanical and Electrical Engineers. under the auspices of Boston Section, A. I. E. E. Attendance 75.

Chicago.—April 26, 1915, Monadnock Block. Address by Mr. W. L. R. Emmet on " Electric Ship Propulsion." Joint meeting with Western Society of Engineers. Attendance 150.

Cleveland.—April 19, 1915, Chamber of Commerce Building. Paper: "Electric Starting and Lighting Systems for Automobiles," by Alexander Churchward. Attendance 47.

Detroit-Ann Arbor.—April 23, 1915, Detroit Engineering Society Club Rooms. Paper: " Automatic Telephony," by S. Hirsch, illustrated by lantern slides. Attendance 45.

May 14, 1915, Engineering Building, University of Michigan, Ann Arbor. Paper: " Wireless Telegraphy," by H. S. Sheppard. Paper was illustrated by lantern slides, followed by demonstrations in the University of Michigan Wireless Experiment Station. Attendance 60.

Fort Wayne.—April 22, 1915, Fort Wayne Electric Works. Address by Mr. O. C. Wright on " Electric Welding as Applied in Railroad Repair Shops." Attendance 24.

Indianapolis-Lafayette.—April 20, 1915, Indianapolis. Paper: " Rural Electrical Development in Indiana," by A. R. Holliday. Attendance 48.

Ithaca.—April 30, 1915, Franklin Hall, Cornell University. Paper: " The Heating and Ventilation of Electrical Machinery," by Alexander Gray, illustrated with lantern slides. Attendance 45.

Los Angeles.—April 20, 1915, Chamber of Commerce. Paper: " Application of Electrical Devices to Grade Crossing Protection," by J. A. Bell. Attendance 35.

Panama.—April 25, 1915, Administration Building, Balboa Heights, C. Z. Paper: " The Construction and Some Operating Features of the Trans-Isthmian Underground Telephone and Signal Duct Line," by W. H. Fenley. Also short address by Mr. W. A. Reece on " The Benefits of the Pulmotor in Large Factories." Attendance 15.

Philadelphia.—April 15, 1915, Franklin Institute. Paper: " Control and Protection of Electric Systems," by Dr. Charles P. Steinmetz. Joint meeting with Franklin Institute. Attendance 300.

Pittsburgh.—March 9, 1915, Oliver Building. Papers: (1) " The Manufacture of New Types of Mazda Lamps," by R. E. Myer; (2) " The Use of Projecting Lenses in Signal Work," by H. S. Hower. Joint meeting with Pittsburgh Section of Illuminating Engineering Society. Attendance 140.

Pittsfield.—April 22, 1915, Lenox Hall. Paper: " Educational and Advertising Value of Motion Pictures," by C. F. Bateholts. Attendance 430.

April 29, 1915, Hotel Wendell. Paper: " The Physical Chemistry of the Blood," by W. R. Whitney. Attendance 70.

Portland.—May 4, 1915, Portland. Paper: " Electricity in the Lumbering Industry," by E. F. Whitney. Attendance 24.

May 10, 1915. Address by Dr. E. B. Rosa on " The Bureau of Standards." Joint meeting of local sections of American Society of Civil Engineers, Oregon Society of Engineers, National Electric Light Association, and A. I. E. E. Attendance 80.

Rochester.—April 23, 1915. Paper: " Metering," by Scott Lynn. Attendance 36.

Schenectady.—April 20, 1915, Edison Club Hall. Paper: " Electricity Supply in Large Cities," by Philip Torchio, illustrated by lantern slides. Attendance 167.

May 4, 1915, Edison Club Hall. Paper: " The Paper Industry," by B. Denver Coppage, illustrated with motion pictures. Attendance 175.

May 17, 1915, Edison Club Hall. Illustrated address by Mr. E. B. Ray-

mond on "Manufacture of Plate Glass." Attendance 190.

Seattle.—April 17, 1915, Tacoma, Wash. Trip of inspection to lumber mills of the St. Paul Tacoma Lumber Company, and the new substation of the City of Tacoma. Attendance 22.

Spokane.—April 16, 1915, Chamber of Commerce Building. Paper: "The Electrolytic Theory of Corrosion of Iron," by L. J. Pospisil. Attendance 24.

St. Louis.—May 12, 1915, Engineers Club. Paper: "The Development of Motor Drive and the Use of Central Station Power in the Steel Industry," by Brent Wiley. Attendance 47.

Toledo.—May 5, 1915, Toledo Commerce Club. Address by Mr. G. E. Kirk on "European Cities Before the War." The speaker showed many views of European cities. Attendance 15.

Urbana.—April 30, 1915, Electrical Laboratory. Paper: "Commercial Storage Batteries," by I. W. Fisk, illustrated with lantern slides. Attendance 68.

Washington.—April 13, 1915, Cosmos Club Hall. Address by Mr. H. A. Hornor on "Mariners' Debt to Electricity." Attendance 60.

May 4, 1915, Bureau of Standards. Visit to U. S. Bureau of Standards; demonstration of equipment. Joint meeting with Washington Society of Engineers. Attendance 300.

Past Branch Meetings

University of Arkansas.—May 11, 1915, Engineering Hall. Papers: (1) "Water Power Survey on White River near Beauer, Arkansas," by J. E. Bell; (2) "Sparks" by D. C. Hopper. Attendance 11.

Armour Institute.—April 27, 1915, Great Northern Hotel. Papers: (1) "Qualifications for Central Station Work," by Mr. Jenkins; (2) "A Few Facts Concerning the Operation of the Chicago Elevated Railroad," by Mr. Jones. Attendance 23.

University of California.—April 14, 1915, Berkeley, Cal. Paper: "Block Signal Equipment for an Electric Railroad," by W. R. Catching. Election of officers for the coming year as follows—chairman, J. V. Kimber; vice-chairman, O. R. Marston; treasurer, W. L. Winter; secretary, H. A. Mulvaney. Attendance 27.

University of Cincinnati.—April 20, 1915. Paper: "Remote Control," by Mr. Warner. Attendance 22.

Clemson Agricultural College.—April 12, 1915, Mechanical Engineering Building. Paper: "Mechanical Stresses due to Currents in Single and Polyphase Lines," by S. R. Rhodes. Attendance 24.

University of Colorado.—April 22, 1915, Engineering Building. Illustrated lecture by Mr. William Trudgian on "The Westinghouse Apprentice Course." Attendance 30.

April 29, 1915, Hale Science Building. Paper: "High-Tension Transmission," by Norman Read. Attendance 23.

May 6, 1915, Engineering Building. Paper: "The Control of Lock Machinery at the Panama Canal," by B. C. J. Wheatlake. Attendance 30.

Colorado State Agricultural College. April 28, 1915. Papers: (1) "Methods of Rail Bonding"; (2) "Use of Reactance in Power Circuits"; (3) "Needle Point vs. Sphere Gap." Attendance 12.

University of Idaho.—May 5, 1915, Administration Building. Illustrated address by Mr. Olsen on "Oil Switches". Paper: "The Fixation of Atmospheric Nitrogen," by L. L. Summers. Attendance 25.

University of Kentucky.—April 28, 1915, Mechanical Hall. Paper: "Street Lighting and Park Lighting," by W. M. Hannah. Attendance 38.

Lehigh University.—April 16, 1915, Physics Lecture Room. Papers: (1) "Motors as Applied to Industries," by H. L. Vitzthum; (2) "The Electromagnet," by C. R. Underhill. Attendance 37.

Montana State College.—April 24, 1915, Engineering Reading Room. Address by President J. M. Hamilton on "The Opportunities of the Electrical Engineer." Election of officers for the coming year as follows—president, Taylor Lescher; secretary, J. A. Thaler. Attendance 34.

University of Nebraska.—May 13, 1915, Electrical Building. Subject: Aeronautics. Addresses by Messrs. R. C. Greer and I. K. Frost. Election of officers for the coming year as follows—chairman, O. J. Ferguson; secretary, V. L. Hollister; student chairman, F. W. Norris; student treasurer, R. W. McCullough; student secretary, J. Buchta. Attendance 27.

North Carolina College of Agricultural and Mechanical Arts.—April 20, 1915. Demonstration of laboratory-built Tesla transformer by Messrs. Jeffers and Cox. Attendance 25.

April 27, 1915, West Raleigh. Election of officers for the coming year as follows—president, L. B. Jenkins; vice-president, R. L. Kelly; secretary-treasurer, E. A. Hester. Attendance 29.

Ohio State University.—April 23, 1915, Robinson Laboratory. Papers: (1) "Line Testing," by R. B. Shanck; (2) "Dielectric Strength of Porcelain," by H. G. Siek. Attendance 19.

University of Oklahoma.—April 21, 1915, Engineering Building. Papers: (1) "Status of the Engineer," by C. M. Mackey; (2) "Jitney Bus Situation," by Homer Livergood. Attendance 18.

Oregon Agricultural College.—April 20, 1915, Corvallis, Ore. Addresses by Messrs. C. E. Condit and Frank O. Broili on "The Transmission of Electrical Energy." Attendance 30.

Pennsylvania State College.—April 16, 1915, Electric Laboratory. Address by Dr. Sparks on "The Troubles of a College President." Short talks by Professors Walker, Kinsloe, Moyer and Marshman. Joint meeting of engineering societies. Attendance 200.

April 21, 1915, Engineering Department, Room 200. Illustrated lecture on "Control of Lock Machinery at the Panama Canal." Attendance 30.

May 12, 1915, Engineering Department, Room 200. Illustrated lecture by Prof. Govier on "The Development of the Transcontinental Telephone." Attendance 30.

Rensselaer Polytechnic Institute.—May 11, 1915, Sage Laboratory. Experimental lecture by Messrs. J. A. Terrell and J. W. Bacon on "The Principles and Phenomena of Currents of High Voltage and High Frequency." Election of officers for the coming year as follows—chairman, W. J. Williams; secretary, S. N. Galvin; executive committee, T. M. Snyder, E. Hendry, W. Cravens, W. R. Townsend, J. N. Calkins, and F. M. Colvin. Attendance 75.

Stanford University.—April 29, 1915, Engineering Building. Paper: "The Application of Electricity in the Automobile," by A. L. Vail. Election of officers for the coming year as follows—chairman, A. B. Stuart; secretary, H. J. Rathbun; treasurer, M. P. Baker; librarian, N. J. Mittenthal. Attendance 14.

Syracuse University.—May 6, 1915. Paper: "The Evolution of Wireless Telegraphy," by I. Shibuta. Attendance 15.

University of Texas.—April 2, 1915. Papers: (1) "Electric Railway Locomotives," by E. B. Robertson; (2) "Collecting Devices," by R. P. B. Thompson; (3) "Mine Locomotives," by R. M. Keck. Attendance 19.

April 16, 1915. Paper: "The Selection of the Proper Voltage for Electrical Transmission," by Lamar Lyndon. Attendance 35.

April 30, 1915. Papers: (1) "The Eye and Illumination," by L. K. Delhome; (2) "School Illumination," by W. E. Brown; (3) "Factory Lighting," by Elmer Smith. Attendance 19.

University of Washington.—April 14, 1915, Good Roads Building. Papers:

(1) " Electrical Still for the Fractional Distillation of Wood Tar," by B. Sorenson; (2) " Engineering as a Profession," by A. A. Miller. Attendance 30.

May 4, 1915, Good Roads Building. Illustrated address by Prof. L. F. Curtis on " Our Outside Laboratories." Attendance 15.

Yale University.—March 19, 1915, New Haven. Paper: " The Oscillograph," by Clifford W. Bates. Attendance 90.

April 23, 1915, Electrical Laboratory. Paper: " Electromagnets and Their Applications," by Charles R. Underhill. Attendance 95.

Personal

MR. P. J. MURPHY, engineer with Ford, Bacon and Davis, has been elected vice-president and general manager of the Lackawanna and Wyoming Valley Railroad Company, with offices at Scranton, Pa.

MR. GEORGE S. IREDELL has reentered into private practise as civil and electrical engineer, with offices at 521 Littlefield Building, Austin, Texas. Mr. Iredell, who had served successfully for almost eight years as engineer for the city government of Austin, resigned from that position on March 31st.

MR. L. O. VESER has been appointed electrical superintendent of the Massena, N. Y., works of the Aluminum Company of America. Mr. Veser is a graduate of Cornell University and until recently was electrical engineer for the Northern Ohio Traction and Light Company, Akron, Ohio. Previous to this he was associated with the Mahoning and Shenango Railway and Light Company and with the West Penn Traction Company, and had spent several years in Utah and Oregon on hydroelectric work.

Obituary

OWEN C. F. HAGUE of McGill University, Montreal, Lieutenant in the Canadian forces, died of wounds received in action, in Belgium, on May 3, 1915. Lieut. Hague was born in Montreal February 28, 1889. After preparatory training in Montreal High School, he studied at McGill University, and received the degree of B. Sc. in Electrical Engineering in 1909. For the following two years he was an engineering apprentice with the Canadian Westinghouse Company at Hamilton, Ontario, and then began his work at McGill University for the M. Sc. degree and as demonstrator in the Electrical Laboratory.

Lieut. Hague was elected an Associate of the Institute on June 27, 1912.

FREDERICK STARK PEARSON, D.Sc., Mem. A.I.E.E., president of the Pearson Engineering Corporation, Ltd., was one of the Americans who lost their lives when the steamship *Lusitania* was torpedoed and sunk by a German submarine off the coast of Ireland on May 7, 1915. Dr. Pearson was born July 3, 1861, in Lowell, Mass., and received his technical education at Tufts College as a civil engineer, afterwards taking post-graduate courses in mechanical and electrical engineering, and a special course in mining engineering and chemistry. Subsequently he was an instructor in chemistry at the Massachusetts Institute of Technology and instructor in higher mathematics and mechanical engineering at Tufts College. Then he was successively manager of the Somerville Electric Light Company, treasurer and manager of the Woburn Electric Light Company, and the Halifax Electric Light Company. Becoming interested in the construction of electric street railways, he was chief engineer of the West End Street Railway Company and consulting engineer for the Brooklyn City Railroad Company. On October 25, 1892, Dr. Pearson was elected an Associate of the

Institute, and on February 21 of the following year he was transferred to the grade of Member. Dr. Pearson's constructive engineering achievements have been so numerous and extensive that it is impossible to mention them all. His engineering direction has enlisted the support of American and foreign bankers in the formation of great companies such as the Brazilian Traction, Light and Power Company, electrical generating companies in and around Mexico City, Barcelona, Spain, Niagara Falls and Toronto, Ontario, Winnipeg, Manitoba, and railroad, milling and mining companies in northwestern Mexico. Dr. Pearson in recent years lived much of his time abroad. He also had a home in Great Barrington, Mass.

Recommended for Transfer, May 14 and 17, 1915

The Board of Examiners, at its meetings on May 14 and May 17, 1915, recommended the following members of the Institute for transfer to the grades of membership indicated. Any objection to these transfers should be filed at once with the Secretary.

TO THE GRADE OF FELLOW

McCROSKY, JAMES WARREN, Consulting Engineer, New York, N. Y.

PALMER, RAY, Commissioner of Gas and Electricity, Chicago, Ill.

PUPIN, MICHAEL I., Professor of Electro-Mechanics, Columbia University, New York, N. Y.

TO THE GRADE OF MEMBER

ACHATZ, RAYMOND VINCENT, Instructor in Telephone Engineering, Purdue University, Lafayette, Ind.

BLAKESLEE, HENRY J., Treasurer and Electrical Engineer, The States Co., Hartford, Conn.

EKERN, EMIL ALFRED, Hydro-electrical Engineer, c/o Charles T. Main, Great Falls, Mont.

HUDSON, RALPH G., Instructor of Electrical Engineering, Massachusetts Institute of Technology, Boston, Mass.

JOHNSON, CLARENCE G., Chicago, Ill.

KREMER, WALDEMAR R., Advisory Electrical-Mechanical Engineer, Vilter Mfg. Co., Milwaukee, Wis.

LANE, WILLIAM CARL, Professor of Electrical Engineering, Oklahoma Agri. and Mech. College, Stillwater, Okla.

MACCUTCHEON, ALECK M., Engineer in Charge of Design, Reliance Electric Co., Cleveland, O.

NEWTON, GEORGE J., Designing Engineer, with G. M. Gest, New York, N. Y.

ROSE, WILLIAM H., Captain, Corps of Engineers, U. S. A.; Electrical Engineer, Panama Canal, Balboa Heights, C. Z.

SCOTT, HAMILTON G., General Manager, Virginian Power Co., Charleston, W. Va.

SUTTOR, JOHN B., JR., Manager, Australian General Electric Co., Sydney, N. S. W.

TANNER, HARRY L., Engineer, Sperry Gyroscope Co., Brooklyn, N. Y.

WATSON, ARTHUR EUGENE, Professor, Brown University, Providence, R. I.

WHITE, FRANCIS J., Electrical Engineer, Okonite Co., New York, N. Y.

Fellow Elected May 18, 1915

WATSON, THOMAS AUGUSTUS, 67 Mt. Vernon St., Boston, Mass.

Transferred to the Grade of Member May 18, 1915

The following Associate was transferred to the grade of Member of the Institute at the meeting of the Board of Directors on May 18, 1915.

POWELL, PERCIVAL HERBERT, Lecturer in Electrical Engineering, Canterbury College, Christchurch, New Zealand.

Members Elected May 18, 1915

FONDILLER, WILLIAM, Electrical Engineer, Western Electric Co.; res., 24 Charles St., New York, N. Y.

GUY, GEORGE L., Consulting Electrical Engineer, 789 Broadway Ave., Winnipeg, Canada.

HOWE, CHARLES SUMNER, President, Case School of Applied Science, Cleveland, Ohio.

KANE, JOHN J., Patent Attorney, Allis-Chalmers Manufacturing Co., Milwaukee, Wis.

PONTECORVO, LELLO, Director and Manager, Societa Italiana Westinghouse, Vado, Ligure, Italy.

SMITH. AUGUSTUS CANFIELD, Sales Engineer, Cataract Power & Conduit Co., Buffalo, N. Y.

Associates Elected May 18, 1915

BAIRD, HOBART B., Electrical Engineer, Hagerstown and Frederick Railway Co., Hagerstown, Md.

*BELL, WILLIAM R., Chief Load Despatcher, Connecticut River Transmission Co., Millbury, Mass.

BLANEY, LLOYD W., Wireman, Panama Canal, Gatun, C. Z.

CHAMPAGNE, LEO J., Electrical Engineer, Los Angeles County, Hall of Records; res., 1000 W. Pico St., Los Angeles, Cal.

CHAPMAN, PAUL EDWIN, Asst. to Gen'l. Supt. Elec. Distribution, Pacific Gas & Electric Co., 5th and Tehama Sts., San Francisco, Cal.

*CHUNG, DANIEL McCLEAN, Apprentice Electricity Dept., Shanghai Municipal Council; res., 156 N. Szechuen Rd., Shanghai, China.

COLLINS, JOSEPH F., Consulting Engineer, 308 Walnut St., Philadelphia, Pa.

CONWELL, ROLLIN N., Laboratory Assistant, Public Service Electric Co., Newark; res., 176 Berkeley Ave., Bloomfield, N. J.

CORY, MERTON M., Instructor in Electrical Engineering, Michigan Agricultural College, East Lansing, Mich.

DANNER, J. RUSSELL, Apprentice Electrical Engineer, Braden Copper Co., Rancagua, Chile, S. A.

DASH, CYRUS C., Instructor in Electrical Engineering, Case School of Applied Science, Cleveland, Ohio.

FISH, JAMES A., Switchboard Operator, Alabama Power Co., Gadsden, Ala.

FLYNN, A. A., Electrical Engineer, Rogue River Public Service Corp., Gold Hill, Ore.

*GOKAY, WILLIAM M., Foreman, Electrical Construction, Eastern Michigan Power Co., Jackson, Mich.

HAIG, WILLIAM A., JR., City Electrical Inspector, City Hall; res., 690 28th St., Milwaukee, Wis.

HAUSEN, RAYMOND F., Partner, Pittsburgh Carbon Brush Co., & R. F. Hausen Co., 518 Sandusky St., N. S. Pittsburgh, Pa.

IENGAR, NUGIHALLI N., Electrical Engineer, 4 Sheshadripuram, Bangalore, India.

JOSSELYN, BENAGE S., JR., Repair Dept., General Electric Co., 365 E. Illinois St., Chicago, Ill.

*KNIGHT, IRA W., Engineer, Boston Office, Underwriters' Laboratories, Inc., 87 Milk St., Boston, Mass.

*MACKENZIE, ALEXANDER M., Wire Chief, Bell Telephone Co.; res., 53 Glasgow St., Guelph, Ont.

MACQUEEN, JAMES ARCHIBALD, Assistant Superintendent, Schumacher Gray Co.; res., Suite 18, Scott Apts., Maryland St., Winnipeg, Man.

MAHER, HARRY L., Electrical (Experimental) Dept., Ford Motor Co.; res., 214 Hague Ave., Detroit, Mich.

MALBY, SETH G., Eng. Salesman, Aluminum Co. of America; res., 96 Claremont Ave., New York, N. Y.

McGAHEY, CALVERT R., Electrical and Mechanical Engineer, 208 Coca Cola Bldg., Baltimore, Md.

MINTON, JOHN P., Electrical Research, General Electric Co.; res., Y. M. C. A., Pittsfield, Mass.

MULDAUR, GEORGE BARTON, Manager, Field Cooperation, Society for Electrical Development, 29 W. 39th St., New York, N. Y.

NEBLETT, HERSCHEL W., Draftsman, Commonwealth Edison Co., Room 600, 72 W. Adams St., Chicago, Ill.

OHLSSON, FRITZ S., Superintendent of Central Station, Municipal Light and Water Plant, Elkhorn, Wis.

PERHAM, DOUGLAS McD., Electrician, 105 Second Ave.; res., 1007 H Ave.W., Cedar Rapids, Iowa.

PHIPPS, AUGUSTIUS H. Q., Engineer in Charge, Power House, B. C. Electric Ry. Co., Goldstream, B. C.

RAMSEY, HAROLD E., Junior Electrical Engineer, Div. of Valuation, Interstate Commerce Commission; res. 813 Mass. Ave. N. E., Washington, D.C.

RINDFLISH, FRED C., Electrical Draftsman, Ford Motor Co.; res., 417 3rd Ave., Detroit, Mich.

ROESLER, GEORGE A., Chief Engineer, Englewood Power Station, Homestake Mining Co., Englewood, S. D.

ROTH, HENRY C., Supervising Engineer of Construction Work, with A. C. Moore; res., 327 N. Wall St., Joplin, Mo.

ROWE, EUGENE C., Draftsman, Commonwealth Edison Co., Room 620, 72 W. Adams St., Chicago, Ill.

SANFORD, DUDLEY, Operator, Utah Power & Light Co., Grace, Idaho.

SCHMIECH, CARL A., Roadman, General Electric Co.; res., 1033 N. Dearborn Ave., Chicago, Ill.

SKOVE, WALTER, Switchboard Operator, Cleveland Municipal Electric Light Plant; res., 11716 Woodland Ave., Cleveland, Ohio.

SMITH, JAMES U., Head Draftsman, Mech. & Elec. Dept., Panama-Pacific International Exposition, San Francisco; res., 2320 Ward St., Berkeley, Cal.

STENGEL, CHARLES, Manager, Municipal Light and Power Plant, Wolseley, Sask.

STEPHENS, HARRY H., Secretary and Engineer, D'Olier Centrifugal Pump & Machinery Co.; res., 5106 Warnock St., Logan, Philadelphia, Pa.

TANZER, E. DEAN, Assistant Professor of Electrical Engineering, Lafayette College; res., Mattes Lane, College Hill, Easton, Pa.

THOMSON, GEORGE L. A., Laboratory Assistant, Public Service Electric Co., Newark; res., 852 Kilsyth Rd., Elizabeth, N. J

TURNBULL, WILLIAM H., JR., Substation Inspector, West Jersey and Seashore R. R. Co., Pennsylvania R. R. Co.; res., 74 Centre St., Woodbury, N. J.

*WHITALL, ROY C., Engineer, Whitall Electric Co., Westerly, R. I.

WILLIAMS, ROBERT GEORGE HAND, Chief Testing Engineer, Electric Cable Co., Bridgeport, Conn.

Total 46.

*Former enrolled students.

Applications for Election

Applications have been received by the Secretary from the following candidates for election to membership in the Institute. Unless otherwise indicated, the applicant has applied for admission as an Associate. If the applicant has applied for direct admission to a higher grade than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the Secretary before June 30, 1915.

Arnold, C. N., Chicago, Ill.
Baily, P., Atlantic City, N. J.
Birch, A. L. (Member), Kuala, India.
Calman, C. G., Melbourne, Australia.
Coley, R. J., Toronto, Ont.
Cruikshank, J. S., Baltimore, Md.
Elkins, L. R., New York, N. Y.
Emory, F. D., Kaslo, B. C.
Freese, R. J., Brooklyn, N. Y.
Freund, C. J., Pittsburgh, Pa.
Glover, E. B., Erie, Pa.
Goldman, F., Portland, Ore.
Holland, M., Boston, Mass.
Linnell, C. G., Massena, N. Y.
Lubienski, H., Petrograd, Russia
Means, E. C. (Member), Denver, Colo.
Nimmo, W. H. R., Hobart, Tasmania.
Oehrig, H. B., Newark, N. J.
Pawson, H. E., Prince Albert, Sask.
Pennington, P., New York, N. Y.
Reeve, C. T., Cohoes, N. Y.
Reisfeld, L., Chicago, Ill.
Rohland, C. J., Worcester, Mass.

Shuler, W., Jr., Cleveland, O.
Smith, H. F., New York, N. Y.
Snyder, C. C., Fellows, Cal.
Stevens, W. H., Balboa, C. Z.
Thompson, J. T., New York, N. Y.
Trainer, J. E., New York, N. Y.
Weiser, R. G., Brooklyn, N. Y.
Wheeler, R. N., Porcupine, Ont.
Wheeler, W. S. (Member), New York, N. Y.
Wilhelm, G. T.. Denver, Colo.
Zencak, F., Philadelphia, Pa.
Total 34.

Students Enrolled May 18, 1915

7331 Kimber, J. V., Univ. of Cal.
7332 Jackson, W. D.. Ohio Nor. Univ.
7333 Parkinson, W. S., Jr., Penna. State College.
7334 Purdy, A. R., Cornell Univ.
7335 Gilcher, R. J., Cornell Univ.
7336 Boland, C. S., Ga. Inst. Tech.
7337 Locke, G. A., Cooper Union.
7338 Frank, T. L., Univ. of Nebr.
7339 Locke, E. A., Tufts College.
7340 Schmitz, H.A., Jr., Marquette Univ.
7341 Burnham, E. J., Univ. of Kans.
7342 Anderson, H. R., Norwich Univ.
7343 Ryder, L. E., Norwich Univ.
7344 Foskett, E. L., Norwich Univ.
7345 Merkel, W. C., Norwich Univ.
7346 Brown, N. F., Univ. of Mich.
7347 Dellinger, L. M., Univ. of Mich.
7348 Barnes, L. A., Univ. of Nebr.
7349 Potts, W. A., Stanford Univ.
7350 Ferguson, J. G., Univ. of Calif.
7351 Lescher, T.T., Montana State Col.
7352 Eshleman, G.J.C., Penna. St. Coll.
7353 Stoup, G.A., Case School App. Sci.
7354 Zimmerman, H. J., Case School of Applied Science.
7355 Miller, E. C., Univ. of Wash.
7356 Smith, G. S., Univ. of Wash.
7357 Smith, U. M., Univ. of Mich.
7358 Taylor, A. N., Univ. of Toronto.
7359 Fenker, C. M., Univ. of Cin.
7360 Grass, S. A., Penna. State Coll.
7361 Bell, E. D., Univ. of Illinois.
7362 Ironside, G.A., Univ. of Toronto.
7363 Smith, R. K., Purdue University.
7364 Hockaday, O. S., Univ. of Texas.
7365 Tays, E., Univ. of California.
7366 Burgett, L. S., Case Sch. App. Sci.
7367 Brown, E. A., Univ. of Illinois.
7368 Miller, J. H., Univ. of Illinois.
7369 Davidson, G. P., Univ. of Toro.
7370 Adams, T. J., Univ. of Virginia.
7371 Birren, E. G., De Pauw Univ.
7372 Peebles, J. K.. Jr., Univ. of Va.
Total 42.

EMPLOYMENT DEPARTMENT

NOTE: Under this heading brief announcements (not more than 50 words in length) of vacancies, and men available, will be published without charge to members. Copy should be prepared by the member concerned and should reach the Secretary's office prior to the 20th of the month. Announcements will not be repeated except upon request received after an interval of three months, during this period names and records will remain in the office reference files. All replies should be addressed to the number indicated in each case, and mailed to Institute headquarters.

The cooperation of the membership by notifying the Secretary of available positions, is particularly requested.

Vacancies

The United States Civil Service Commission announces an open competitive examination for electrical engineer and draftsman on June 23 and 24, 1915, to be held at numerous places in the United States. From the register of eligibles resulting from this examination certification will be made to fill vacancies as they may occur in this position at $1,200 a year, in the office of the Supervising Architect, Treasury Department, Washington, D. C., and in positions requiring similar qualifications.

Applicants must have the equivalent of a high-school education, and not less than three years' special experience as a draftsman principally in connection with electrical work and illumina-

ting engineering, or be technical graduates with not less than six months' experience as electrical draftsman or practical experience in the installation of electrical wiring or apparatus.

Persons who meet the requirements and desire this examination should at once apply for the circular announcing this examination (Form No. 461, issued May 18, 1915) and Form No. 1312, stating the title of the examination for which the form is desired, to the United States Civil Service Commission, Washington, D. C. Application forms may also be obtained from the secretary of the U. S. Civil Service Board at any of the places where the examination will be held, and if it appears to an applicant desiring this examination that it will not be possible to obtain the necessary forms from the Commission at Washington in time, it is suggested that inquiry be made at the nearest post office or custom house.

Men Available

281. Electrical Engineer. Graduate of leading Eastern technical school, 1914. Would like to locate with some manufacturing or construction company where practical experience may be obtained. For past six months have been employed as salesman of electric apparatus.

282. Electrical Engineer. Seven years with large light and power companies in France; three years with G. E. Co. at Schenectady; five years representing large companies manufacturing electrical apparatus in France and Spain. Speak French, Spanish, English and Russian. At present manager of power plant in Paris. Desires position as representative of an American firm in Europe or South America.

283. Electrical Engineer. Married; age 31. Seventeen years' experience, comprising electric railway, substation, power plant, high and low tension installations, electric furnaces. Thoroughly understand installation and operation. Have executed considerable work requiring much originality of design.

284. Electrical Engineer. 5½ years' practical experience in design, construction and operation of power plants, substations and transmission lines; 2½ years' experience on steam railway electrification project in calculation of electric energy requirements and design of transmission lines, substations, powerhouses and determination of other requirements.

285. Engineer. Two years' experience as engineer of steam turbine plant. Ten years as draftsman, designing and field construction engineer on power plants, transformer and rotary converter stations, transmission and distributing systems. Good civil and mechanical engineer with an excellent knowledge of inorganic chemistry. Present location Toronto, Canada.

286. Electrical and Mechanical Engineer. Graduate Sheffield, 1910. One year's practical experience in Lynn shops of General Electric Co. Three years designing automatic telephone apparatus for Western Electric Co. Thoroughly familiar with present-day manufacturing methods. Desires opportunity with smaller concern.

287. Electrical Engineer. Five years' experience in central station construction and operation; with steam and hydraulic high-tension transmission construction and operation; d-c. operation and distribution. General office experience, including operating and cost data. Good draftsman and chemist. Age 29; married; university and technical training. Salary secondary consideration.

288. Electrical Engineer. Age 24; 1914 graduate. Desires position with light and power company. One year's experience with high voltage transmission lines, including insulator testing. Some experience with electric steel furnace. Speaks English, Spanish and Portuguese.

289. Electrical and Mechanical Engineer. Age 32; married. Twelve years' experience, from coal pile to switchboard. Can analyze coal and get best results from it. Possess CO_2 recorder and steam engine indicator. Wide experience in erecting heavy electric machinery. Willing to start on very moderate salary provided chance for advancement is afforded.

290. Electrical Engineer. R. P. I. graduate; married. Five years' experience as electrical contractor, two years with the New York State Public Service Commission as construction inspector. Very broad practical experience in electrical, steam and mechanical engineering. Desires position, preferably out of New York City, where ability and hard work will be rewarded.

291. Manager or technical director capable of handling complete enterprise. Business changes make a technical graduate, electrical engineer, (Columbia, 1897) available for opportunity where a salary of $5000 a year is to be earned, part of which may be contingent. Experience covers full charge of

purchasing material and executing contracts; manufacturing; and financial work.

292. Electrical Engineer. Technical graduate of western university of recognized standing (1910). Experience includes one and a half year G. E. test and laboratory work and more than two years designing transformers, mostly for special purposes, such as testing, etc. Have had some construction and drafting room experience.

293. Technical Graduate, (E. E.), with five years' practical experience in large western electric and ice machine company. Experience embraces jig and fixture design, estimating, analysis of production costs, d-c. electrical design, and machine shop work. Desires employment with engineering or manufacturing company. At present employed.

294. Electrical Engineer. Age 29; married. Seven years' experience as electrical worker, draftsman, Westinghouse test, research and development. Formerly assistant engineer handling industrial applications. Possess initiative and executive ability. Desire permanent connection in sales, manufacturing or consulting work. Can invest capital; available upon reasonable notice; salary $1500.

295. Technical Graduate. Ten years' experience in gas and electrical manufacturing, light and power work. Desires change to engineering or executive position in electric lighting or combination company.

296. An experienced and successful teacher of electrical engineering is available for school year beginning September 1. Five years' experience in design, construction and operation of power plants; four years' teaching experience in large university. One book largely used as a text in engineering schools; another issued this spring.

297. Engineer. Electrical graduate with six years' experience designing and constructing electrical distributing apparatus, wiring, inspection of installations, operation of all types of electrical machinery. Age 29. Middle West preferred.

298. Electrical Engineer. Rensselaer and Mass. Inst. Tech. and Westinghouse engineering apprenticeship course. Age 34. Ten years' experience in railway electrification work, powerhouse and boiler-room efficiency work. Experienced in engineering, construction and operation. Capable of assuming executive charge or superintending design or construction.

299. Telephone Engineer and Superintendent with proven construction maintenance and business experience, desires position with reliable firm in the East. Also considerable sales experience. Can aid you to make your business more efficient and profitable. Said to be very thorough by those who know him.

300. Electrical Engineer, technical graduate, desires connection with consulting engineering or research organization. Experience with original investigations of high and low voltage transmission and station problems, preceded by commercial and research testing at manufacturing plant. Specialist on transmission and induction troubles and oscillograph investigations.

301. Electrical Engineer. Technical graduate, 1913. Two years General Electric test. Would like to locate with construction or central station company where practical experience may be obtained. Now employed.

302. Technical Graduate, 1911. Two years with consulting engineer as assistant and then principal. Central heating and power plant; equipment of buildings and factories. At present employed laying out equipment for additions and alterations to present installation in factory; work now practically completed. Desires permanent position.

303. Contract Engineer and Solicitor. Specialist in applying electricity to manufactories. Fifteen years' experience in industrial engineering. Past five years and at present engaged in making tests and reports on factory power plants and equipment to show superiority of central station power. Desire similar position with Eastern concern.

Library Accessions

The following accessions have been made to the Library of the Institute since the last acknowledgment.

Detroit. Board of Street Railway Commissioners. Report on Detroit Street Railway Traffic and Proposed Subway. By Barclay Parsons & Klapp. New York, 1915. (Gift of authors).

Electricity for the Farm. By F. I. Anderson. New York, The Macmillan Co., 1915. (Gift of Publisher). Price, $1.25.

A book not for engineers, but for farmers; written in very plain language. Tells of the

installation of small hydro-electric and gasolene electric plants; transmission lines, wiring buildings for power and light and care of storage batteries. No discussion of wind-mill driven installations, so common abroad, is given.

W.P.C.

Maryland. Public Service Commission. Report 1914. Baltimore, 1915. (Gift of Maryland Public Service Commission).

The Parshall Family, A.D. 1870-1913. A collection of historical records and notes to accompany the Parshall pedigree. By Horace Field Parshall. London, 1915 (Gift of Author).

On the Precision Measurement of Air Velocity by Means of the Linear Hot-wire Anemometer. By L. V. King. (Reprint from Philosophical Magazine, Apr. 1915). (Gift of author).

Public Utilities; their fair present value and return. By Hammond V. Hayes. N. Y. Van Nostrand Co., 1915. (Gift of Publisher). Price, $2.00.

This supplements the work of the same author published last year, which treated of the "cost new and depreciation" of public utilities. The treatment of the question of the proper interpretation of overhead charges is unusual.

W.P.C.

GIFT OF J. J. BELLMAN.

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General Electric Company. Schenectady N. Y. Bull. 41013. Direct current commutating pole motors, Type RC. March 1915.

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——Bulletin 24. Outdoor tennis court lighting.

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Supplee-Biddle Hardware Co. Philadelphia, Pa. Monel Metal. April 1915.

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Under Feed Stoker Co. Chicago, Ill. Publicity Magazine. April 1915.

UNITED ENGINEERING SOCIETY.

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Anthracite Coal Combination in the United States. By Eliot Jones Cambridge, 1914. (Purchase.)

The Bells of Lynn. By C. J. H. Woodbury. (Paper given before the Lynn Historical Society, Dec. 10, 1914.) Lynn, 1915. (Gift of author.)

Beton Kalender Taschenbuch für den Beton und Eisenbetonbau, X. Jahrgang, 1915, pts. 1-2. Berlin, 1914. (Purchase.)

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Canadian Mining Manual, 1914. Toronto, 1914. (Purchase.)

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Total 52.

SECTION II

PROCEEDINGS

of the

American Institute

of

Electrical Engineers

Papers, Discussions and Reports

CONTENTS OF SECTION II

PAPERS TO BE PRESENTED AT 32nd ANNUAL CONVENTION, DEER PARK, MD., JUNE 29—JULY 2, 1915.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

I—FORM FACTOR AND ITS SIGNIFICANCE

BY FREDERICK BEDELL

ASSISTED BY R. BOWN AND H. A. PIDGEON

ABSTRACT OF PAPER

Form factor is significant in the study of transformer losses; as is well known, hysteresis loss is small when the form factor is large and *vice versa*. Every wave shape has a definite value of form factor; but the converse is not true, for a particular value of form factor does not indicate a particular wave shape. A wave may contain a third harmonic equal to seventy five per cent. of the fundamental and still have the same form factor as a true sine wave. Form factor, therefore, has no general significance as an indicator of wave form or wave distortion.

A general expression for form factor is derived in terms of the relative amplitudes and phase positions of its harmonic components; curves are drawn showing the variation of form factor with the amplitude and phase of the third harmonic.

Various wave forms are shown, very unlike in appearance, having the same form factor.

FORM factor, f, is the ratio of the r.m.s. value to the average value of an alternating quantity for half a period. The quantity to which form factor refers is usually an alternating electromotive force, in which case $f = E \div E_{av}$. Each particular wave shape has a definite form factor and so to a certain extent form factor indicates the shape of a wave and its departure from a true sine wave. Thus, a sine wave has a form factor 1.1107; a flat wave has a lesser form factor and a peaked wave a greater. If the converse were true and a particular value of form factor indicated one particular wave shape, the form of a wave could be accurately defined in terms of form factor, but, as will be seen later, this is far from being the case.

It is true that, for certain purposes, the value of form factor is significant, as for example in the determination of transformer losses. Hysteresis loss in a transformer depends upon the maximum value of the magnetic flux. But, inasmuch as the flux ϕ is determined by the relation $\phi \propto \int e dt$, the maximum value

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of the flux is proportional to the average value of e and hence to the r.m.s. value divided by form factor; that is

$$\phi_{max} = (E \div f) \times \text{constant}^1.$$

If a transformer is operated at a specified r.m.s. voltage from supply circuits having different voltage wave shapes, the maximum flux and hence the hysteresis loss will, accordingly, have different values for different form factors, becoming greater as the form factor becomes less and *vice versa*. It is well known

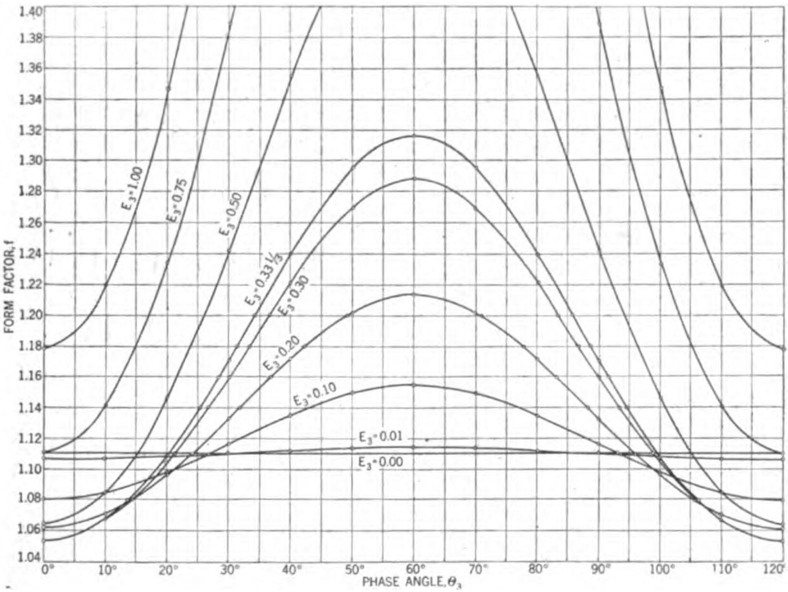

FIG. 1

that a transformer operates less efficiently on a flat wave than on a peaked wave.

If the r.m.s. voltage, E, is increased or decreased in direct proportion to form factor, so that the average voltage, E/f, remains constant, the hysteresis loss in the transformer remains unchanged and this fact is made use of in the determination of transformer losses on a sine-wave basis. For this purpose, the value of form factor can be ascertained by measuring the r.m.s.

1. This constant is 10^8, when E is in volts, divided by 4 $\times$ frequency $\times$ cross section of iron in square centimeters $\times$ number of turns embracing it.

voltage by an ordinary voltmeter and the average voltage by means of a commutator[2] and d. c. voltmeter. To make simple the determination of hysteresis loss on a sine wave basis, without the necessity of determining the value of form factor, a special iron-loss voltmeter[3] has been devised by L.W. Chubb. An advantage in the use of this instrument is that it corrects for small variations in frequency as well as in wave form so as to give the loss for a standard frequency and sine wave form; a small error may be introduced, however, by the fact that eddy current loss and hysteresis loss do not follow the same law.

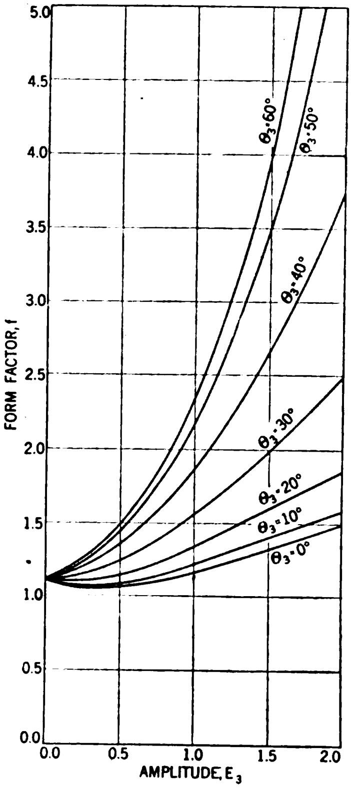

FIG. 2

As has been shown, hysteresis loss depends in a very definite manner upon form factor which, accordingly, *in this connection* has a definite and useful significance. In general, however, form factor has no useful significance as an indication of the shape of a wave or its departure from a sine wave; in fact an irregular wave may have a third harmonic as large as 75 per cent of the fundamental and, if the harmonic is in the proper phase, as will be shown, still have the same form factor as a pure sine wave.

An alternating wave is made up of a fundamental sine wave and harmonics with frequencies that are odd multiples of the fundamental frequency. The form factor of a complex wave depends not only upon the amplitude of these harmonics but upon

2. See, Lloyd and Fisher, "An Apparatus for Determining the Form of a Wave of Magnetic Flux," ***Bulletin Bureau of Standards***, Vol. 4, p. 467, 1908; F. Bedell, The Use of the Synchronous Commutator in Alternating Current Measurements, ***Journal Franklin Institute***, p. 385. Oct., 1913.

3. Method of Testing Transformer Core Losses, Giving Sine-wave Results on a Commercial Circuit, A.I.E.E. TRANSACTIONS, Vol, 28, p. 417, 1909. See also pp. 432-473.

their relative phase positions. The exact value of form factor is determined as follows:

Let E_1, E_3, E_5, etc., be the r.m.s. values of the several harmonics. The r.m.s. value of the total voltage wave is

$$E = (E_1^2 + E_3^2 + E_5^2 + \quad . \quad . \quad .)^{1/2}$$

This comes from the well-known r.m.s. principle[4] that the r.m.s value of any alternating quantity is the square root of the sum of the squares of its harmonic components, irrespective of their phase positions.

To find the average voltage, let the instantaneous voltage be

$e = E_{1max} \sin x + E_{3\,max} \sin 3(x + \theta_3) + E_{5\,max} \sin 5(x + \theta_5) + \,. \,.$, where x is a variable proportional to time; $x = \omega t$.

$$E_{av} = \frac{1}{\pi}\int_0^\pi e dx = -\frac{1}{\pi}\Big[E_{1max}\cos x\Big]_0^\pi$$

$$-\frac{1}{\pi}\Big[\frac{1}{3}E_{3max} \cos 3\ (x + \theta_3)\Big]_0^\pi - \ . \ . \ .$$

$$= \frac{2}{\pi}(E_{1max} + \frac{1}{3}E_{3max} \cos 3\theta_3 + \frac{1}{5}E_{5\,max} \cos 5\ \theta_5 + \ . \ . \ . \ .),$$

$$= \frac{2\sqrt{2}}{\pi}(E_1 + \frac{1}{3}E_3 \cos 3\theta_3 + \ . \ . \ . \ .)$$

The form factor is, accordingly

$$f = \frac{E}{E_{av}} = 1.1107\ \frac{(E_1^2 + E_3^2 + \ . \ . \ . \ .)^{1/2}}{(E_1 + \frac{1}{3}E_3 \cos 3\theta_3 + . \ .)}$$

In this equation E_1, E_3, etc., may represent either r.m.s. or maximum values.

In the following discussion the effect of the third harmonic only will be considered. Corresponding results for any other harmonic may be obtained in a like manner and will vary with the order of the harmonic; but in view of the results here shown and

4. A proof of this principle is given on p. 391, " The Principles of the Transformer," 1896, by F. Bedell.

the fact that the results for any other harmonics would obviously be of the same character, such a laborious study does not seem worth while.

It is seen that form factor varies with the phase as well as with the amplitude of the third harmonic; that is, in the preceding equation there are three variables, E_3, θ_3 and f. Figs. 1, 2 and 3 are plotted by assigning constant values to each one of these

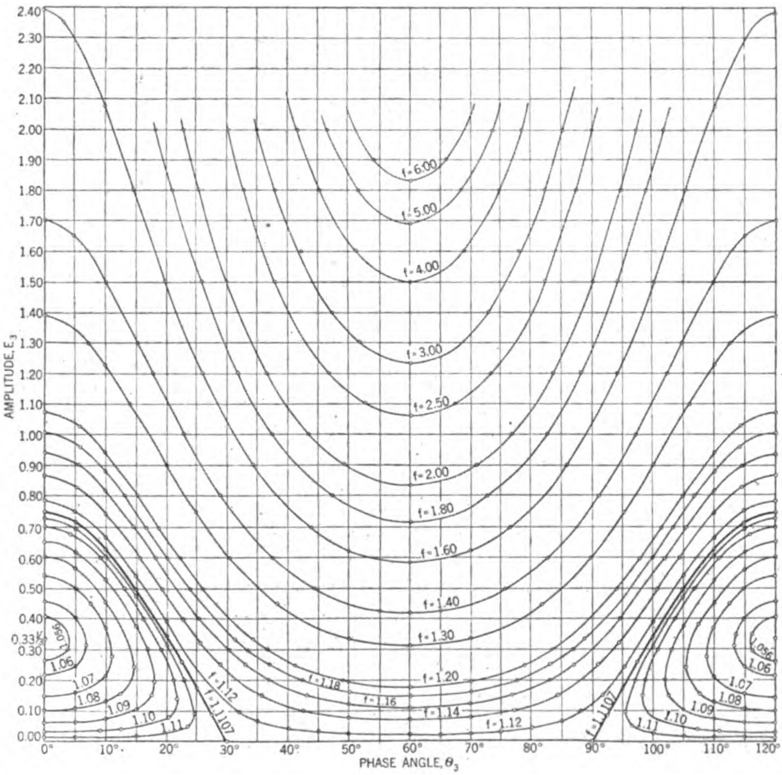

FIG. 3

three variables in turn and evaluating the equation so as to obtain the law of variation between the other two variables. Each figure will be discussed separately; it will be seen, however, that the remarks made in connection with any one figure apply to all.

In Fig. 1, each curve shows the variation of form factor with the phase angle θ_3, of the third harmonic when the harmonic has a definite value, namely, 0, 0.01, 0.10, 0.20, 0.30, 0.33, 0.50,

0.75 and 1.00 times the fundamental. The variation of θ_3 from 0° to 120° represents all possible values, for beyond these limits the curves repeat themselves.

When $E_3 = 0, f = 1.1107$ for all values of θ_3. When $E_3 > 0.75$, $f > 1.1107$ for all values of θ_3. When $E_3 < 0.75$ (the usual case), f may be greater or less than 1.1107, according to the value of θ_3.

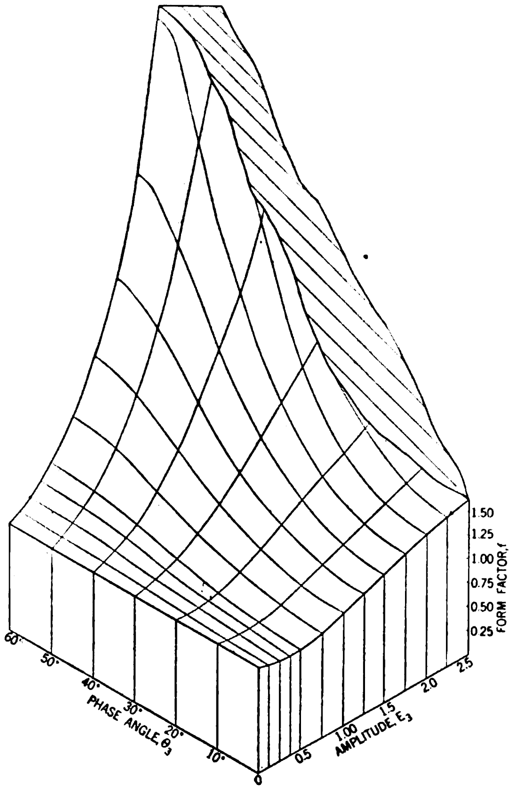

Fig. 4—Variation of Form Factor with Amplitude and Phase of Third Harmonic

The maximum value of f occurs when $\theta_3 = 60$ deg. and this maximum is infinite[5] when $E_3 = 3.00$.

The minimum value of form factor occurs when $\theta_3 = 0$ deg. or 120 deg., and the lowest value of this minimum is 1.0537 when $E_3 = 0.33\frac{1}{3}$. The minimum value is 1.1107 when $E_3 = 0.75$, and is greater than 1.1107 when $E_3 > 0.75$.

5. When $E_3 > 3$, the value of f passes through infinity for two values of θ_3, one greater and one less than 60 deg.

Fig. 2 shows the variation of form factor with the amplitude of the third harmonic, when θ_3 is 0 deg., 10 deg., 20 deg., 30 deg., 40 deg., 50 deg. and 60 deg. As in Fig. 1, it is seen that, when $E_3 = 0$, $f = 1.1107$. When $E_3 < 0.75$, $f < 1.1107$ for small phase angles. The minimum value of f is 1.0537.

In Fig. 3, each curve is drawn for a constant form factor and shows the corresponding relation between E_3 and θ_3. The heavy curve is drawn for $f = 1.1107$, corresponding to a sine wave of

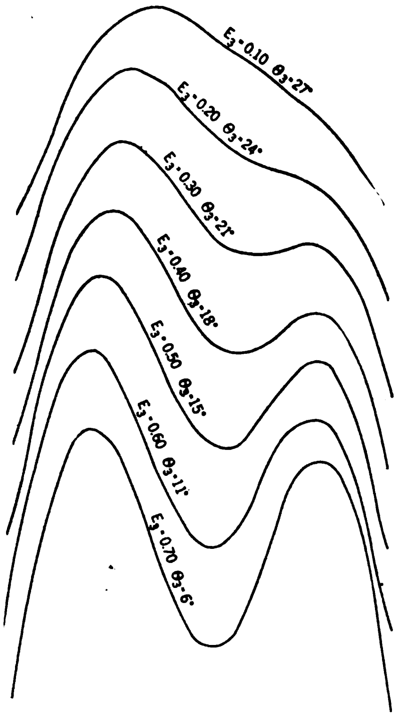

Fig. 5—Waves with Form Factor, $f = 1.1107$

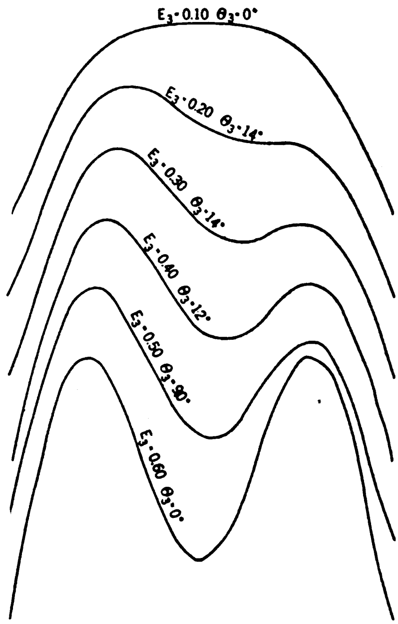

Fig. 6—Waves with Form Factor, $f = 1.08$

electromotive force; E_3 may have any value between 0.75 (when $\theta_3 = 0$ deg. or 120 deg.) and zero. If either $E_3 > 0.75$ or $\theta_3 >$ 30 deg., $f > 1.1107$. A form factor less than 1.1107 is obtained only when $E_3 < 0.75$ and $\theta_3 < 30$ deg. or $\theta_3 > 90$ deg.; for these cases there are two values of E_3 for each value of θ_3. The curves shrink to a single point when f has its minimum value, 1.0537, corresponding to $E_3 = .33\frac{1}{3}$ and $\theta_3 = 0$ deg. or 120 deg.

Fig. 4, drawn in isometric projection, shows the variation of form factor with both E_3 and θ_3. Cross sections of Fig. 4, taken

parallel to each pair of axes in turn, would give curves as shown in Figs. 1, 2 and 3.

To see whether or not there is any similarity of appearance in wave shapes that have the same form factor, Figs. 5, 6 and 7 were drawn by H. Papazian. The wave shapes in each figure have the same form factor, the corresponding values of E_3 and θ_3 being indicated in each case. Fig. 5 shows wave shapes having $f = 1.1107$, the same as a sine wave. Figs. 6 and 7 show wave shapes having $f = 1.08$ and 1.14, a little more and a little less than a sine wave, respectively. The curves show no distinguishing characteristics by which it is possible to tell whether a certain curve has the same form factor as a sine wave or one that is greater or less.

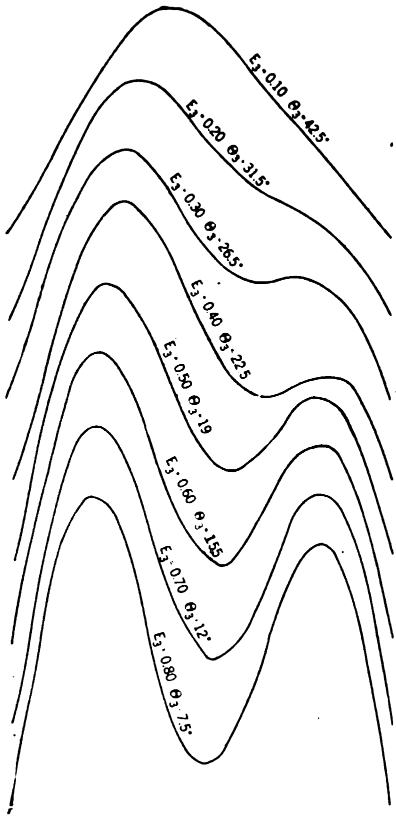

FIG. 7—WAVES WITH FORM FACTOR, $f = 1.14$

The use of five places may seem useless in designating the form factor of 1.1107 for a sine wave, but in plotting the curves here given, particularly those shown in Fig. 3, it was necessary to carry many of the calculations thus far. The results were, in places, inconsistent and unintelligible when computations were less accurate; inspection of Fig. 3 will show that the form factor for a sine wave is a critical value and a slight change in this value makes a great difference in the character of the curve.

In the following paper will be discussed other factors than form factor for indicating the amount of distortion of a wave from a standard sine wave.

To be presented at the 32d Annual Convention of the American Institue of Electrical Engineers, Deer Park, Md., June 29, 1915.

II—DISTORTION FACTORS

BY FREDERICK BEDELL

ASSISTED BY R. BOWN AND C. L. SWISHER

ABSTRACT OF PAPER

A discussion of the significance and usefulness of deviation, peak factor, harmonic factor and curve factor, is followed by a similar discussion of the differential distortion factor δ (which is the distortion factor of the Standardization Rules) and a corresponding integral distortion factor σ defined in this paper. Each factor has its own significance as a numerical measure of the departure of an irregular wave from a pure sine wave and hence has a special usefulness for special purposes, as well as a general usefulness as an indicator of wave distortion. A possible factor combining δ and σ is suggested. The variation of different factors with the phase, amplitude and frequency of harmonics is given. All the factors vary with the amplitudes of the harmonics; some factors are independent of their phase positions, while other factors are independent of their frequencies. Each factor has, therefore, its own characteristics. The importance of δ and σ and their combination is enhanced by the possibility of their use in alternating-current theory and calculation.

THE WAVE shape of an alternating current or electromotive force is completely defined by a curve that shows the value of the current or electromotive force at each instant of time during a cycle. Such a curve contains complete information in regard to the shape of the wave in a way that is satisfactory for many purposes; but it does not give this information in numerical form, convenient for calculation and practical use. Complete information in a numerical form can be given by an equation of the curve,—expressed usually as a series of sine terms,—but such an equation is cumbersome for daily use even in the hands of experts acquainted with its significance, and in the hands of others it is meaningless.

It is desirable, therefore, to be able to define a wave shape,—to a certain extent at least, even if its complete characteristics are not defined,—by a factor, coefficient or percentage which will be convenient to use and readily understood. Such a factor commonly indicates the departure of the wave from some standard, and for a standard a sine wave is generally used.

Manuscript of this paper was received April 9, 1915.

The departure from a standard sine wave may be indicated in a way to be useful for general purposes only, as in case of ***deviation***, or in a way to be useful for some specific purpose, as in case of ***peak factor*** (useful in testing of insulation) or of ***form factor*** (useful in connection with hysteresis loss but without general significance, as discussed in the preceding paper on form factor). These various factors for indicating the amount of wave distortion will be found to have varying degrees of usefulness both in theoretical investigation and in practical application. They are usually employed to indicate the distortion of voltage wave form, but may be used in a like manner to indicate the distortion of a current wave form when occasion arises.

The curve which is compared with the standard sine curve may be the curve of the actual wave itself or it may be the differential or integral of that curve,—as in the case of ***differential distortion factor*** and of ***integral distortion factor*** discussed later. Furthermore, for the standard sine curve of reference we may use the equivalent sine curve, as in the determination of ***deviation***; or we may use the fundamental sine curve, as in the determination of ***curve factor*** and ***harmonic factor***.

It is seen, therefore, that a variety of numerical factors are obtainable each with its own significance. It is the purpose of this paper to bring out certain characteristics of these several factors for comparison and to show the special significance of each, without attempting to give a detailed discussion of their determination or application. It is hoped that this may serve to open a discussion of the treatment of alternating currents of irregular wave shape, both in practice and in theory, by those particularly interested in such treatment. For greatest usefulness, a distortion factor should be definite and determinable, should be convenient as a general measure of wave distortion and should have such a significance that it can be used in making alternating current calculations.

DEVIATION

Deviation is determined by a direct comparison of the wave itself (rather than its differential or integral) with a sine wave of equal r.m.s. value. This sine wave is the equivalent sine wave and is so superposed for comparison that the maximum difference between it and the wave being studied is made as small as possible. Under these conditions, the maximum dif-

ference between corresponding ordinates, divided by the maximum value of the sine wave, is the *deviation*. To obtain deviation, the irregular curve and the equivalent sine curve may be plotted for comparison in rectangular or in polar coordinates, the latter having certain advantages for this purpose pointed out by L. W. Chubb, (TRANSACTIONS, p. 838, Vol. XXXII.).

Although a direct comparison with a sine wave would seem to be the simplest possible measure of deviation, such a comparison in the manner described can only be made by a cut and try process and is not susceptible to simple mathematical analysis. Deviation has a certain obvious common sense meaning but, so far as we can ascertain, its value does not have a significance (such as is possessed by some of the factors discussed later) that can be used in calculation.

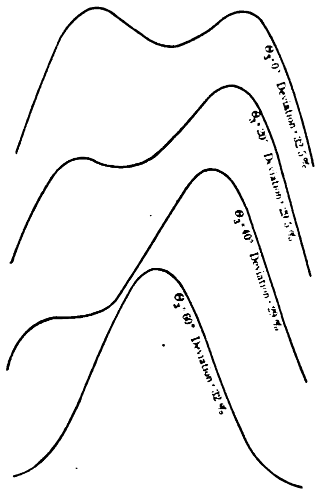

FIG. 1

Deviation indicates the departure from a sine curve in amount but not in kind. It gives no indication whether a wave is peaked or flat, regular or irregular, etc.; waves with the same deviation may have very different form factors, peak factors and differential and integral distortion factors.

Fig. 1 shows four wave shapes, very different in form, consisting of a fundamental and a third harmonic equal to 0.30 of the fundamental placed in various phase positions. The deviation is approximately 0.325 when the phase angle $\theta_3 = 0$; 0.295 when $\theta_3 = 20$ deg.; 0.29 when $\theta_3 = 40$ deg.; 0.32 when $\theta_3 = 60$ deg. It is seen that the deviation is not far from constant and that its value differs but little from the value of the harmonic, 0.30.

The deviation is measured in terms of the equivalent sine wave, while the harmonic is measured in terms of the fundamental sine wave, and these two sine waves are not coincident either in phase or amplitude. The ratio of their amplitudes is the curve factor, discussed later, but there is no simple relation between their phase positions. There is, accordingly, no relation between deviation and the amplitude of the harmonic

or harmonics present that is simple and exact, although as in Fig. 1 the two may be nearly equal when only one harmonic is present.

Deviation is defined in the Standardization Rules of the Institute and although not in extensive use, it has an obvious practical significance.

Curve Factor and Harmonic Factor

Curve factor is the ratio of the r.m.s. value of a wave to the r.m.s. value of the fundamental.

Harmonic factor is the ratio of the r.m.s. value of all the harmonics of a wave, exclusive of the fundamental, to the r.m.s. value of the fundamental.

The term curve factor has been in use, but the term harmonic factor we believe has not.

Let E and E_1 be the respective r.m.s. values of an irregular wave and its fundamental; let E_h be the r.m.s. value of all the component harmonics, taken collectively, without the

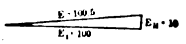

Fig. 2A—Quadrature relation between Fundamental, E_1 and Collective Harmonics, E_h

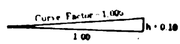

Fig. 2B—Relation between Curve Factor and Harmonic Factor

fundamental. From the r.m.s. principle* that the r.m.s. value of an alternating quantity is the square root of the sum of the squares of the r.m.s. value of its harmonic components, we have the following relations:

$$E_h = (E_3^2 + E_5^2 + E_7^2 + \quad . \quad . \quad .)^{1/2}$$

$$\begin{aligned} E &= (E_1^2 + E_h^2)^{1/2}, \\ &= \left(1 + \frac{E_h^2}{E_1^2}\right)^{1/2} \times E_1, \\ &= (1 + h^2)^{1/2} \times E_1. \end{aligned}$$

The harmonic factor h represents the combined harmonics in terms of the fundamental E_1, taken as unity. It is seen that h is independent of the phase and order of the several harmonics. One harmonic has the same weight as any other and it makes no difference whether many harmonics or only one are present.

*For reference to proof, see the preceding paper on *Form Factor.*

$h \times 100$ is the value of the combined harmonics expressed as a percentage of the fundamental.

From the foregoing, we have

$$\text{Curve factor} = E/E_1 = (1 + h^2).^{1/2}$$

By a convenient approximation,

$$\text{Curve factor} = (1 + h^2)^{1/2} = 1 + (h^2 \div 2).$$

As an illustration, let $E_1 = 100$ and let the collective harmonics be 10% of the fundamental. The harmonic factor then is $h = 0.10$. The curve factor is 1.005 and the r.m.s. value of the total wave is 100.5, as shown in Figs. 2A and 2B. With h known, curve factor can be accurately calculated. The reverse calculation, however, is not so accurate, for a small error in curve factor will make a large error in h.

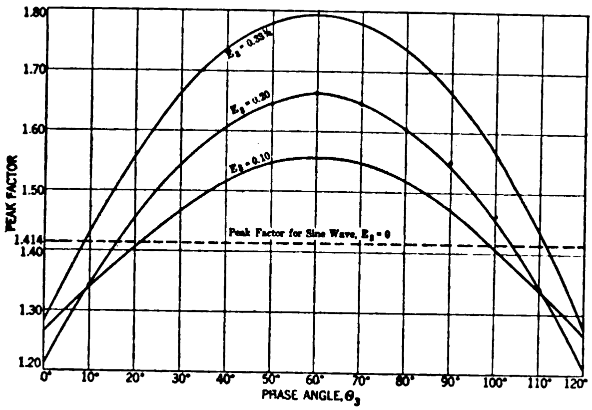

FIG. 3—VARIATION OF PEAK FACTOR WITH PHASE OF THIRD HARMONIC

Curve factor and harmonic factor are useful in their application but difficult in their determination. In an induction motor, the r.m.s. line voltage divided by curve factor gives the fundamental and this alone gives torque to the rotor.

PEAK FACTOR

Peak factor or *crest factor* is the ratio of the maximum to the r.m.s. value and is 1.414 for a sine wave. So far as the third harmonic is concerned, the peak factor will be a maximum when the phase angle $\theta_3 = 60°$ and a minimum when $\theta_3 = 0°$ or 120°, as shown in Fig. 3. The variation of θ_3 from 0° to 120° represents all possible values, for beyond these limits the curves shown in Fig. 3 repeat themselves. A simple expression

for peak factor in terms of the amplitude and phase of the harmonic or harmonics present is, we believe, not obtainable. The curves in Fig. 3 were obtained by a partly analytical and partly graphical process.

Peak factor has an importance in various tests, particularly in insulation testing, and may be calculated from the measured r.m.s. and maximum values. One of the best methods for determining the maximum value of a voltage wave experimentally is to measure with a d-c. instrument and synchronous commutator the current taken by a condenser connected across circuit to be tested.[1]

Differential and Integral Distortion Factors

In an alternating current circuit many effects do not depend directly upon the value of some particular alternating quantity but depend upon the differential or upon the integral of that quantity with respect to time. The value of its differential or integral is, therefore, in many respects of as much importance as the value of the quantity itself. This is the case when a circuit contains inductance or capacity.

When a quantity varies as a sine function of the time, both the differential and the integral of the quantity are likewise sine functions and so have the same wave shape as the original quantity. In the case of an irregular wave, however, its differential and its integral are distorted, each in a particular manner, so as to have wave shapes that differ from the wave shape of the original quantity and from each other. The distortion either of the differential wave or of the integral wave, compared with a sine wave as a standard, may, therefore, be taken as a measure of the distortion of the original wave itself. The two results will be different in their numerical values and in their significance and application.

Based on the foregoing are the following defintions:

The *differential distortion factor* (δ) of a wave is the ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

The *integral distortion factor* (σ) of a wave is the ratio of the r.m.s. value of the integral of the wave with respect to time to the r.m.s. value of the integral of the equivalent sine wave.

1. See Chubb and Fortescue, A. I. E. E. Transactions; Vol. 32, 1913, p. 739; F. Bedell, *Electrical World*, Vol. 62, 1913, p. 378; F. Bedell, *Journal of the Franklin Institute*, Oct. 1913.

It will be seen that the factor δ is the distortion factor as now defined in the Standardization Rules of the Institute. The corresponding factor σ, based on the integral instead of the differential relation, will also, it is believed, be found useful, both in itself and in conjunction with δ. A following paper, by F. M. Mizushi, shows the application of these factors δ and σ and of $1/\delta\sigma = -\cos\Psi$ in obtaining certain solutions for non-harmonic alternating currents. These factors become more desirable as they are given a rational as well as an empirical basis. The significance of δ and σ is brought out in the subsequent paragraphs.

Differential Distortion Factor

Let e be the instantaneous value of an irregular voltage wave and let e' be the instantaneous value of its equivalent sine wave. If x is a variable proportional to time ($x = \omega t$), the differential distortion factor is, by the foregoing definition,

$$\delta = \text{r.m.s.}\ (de \div dx) \div \text{r.m.s.}\ (de' \div dx).$$

The irregular wave, e, may be represented in the well known manner by a fundamental sine term and a series of harmonics; thus,

$$e = E_{1max} \sin x + E_{3max} \sin 3(x + \theta_3) + E_{5max} \sin 5(x + \theta_5) + \ldots$$

Hence,

$$de \div dx = E_{1max} \cos x + 3\,E_{3max} \cos 3\,(x + \theta_3) + E_{5max}\ \cos 5\ (x + \theta_5) + \ldots.$$

By the r.m.s. principle already referred to, we have then

$$\text{r.m.s.}\ (de \div dx) = (E_1^2 + 9E_3^2 + 25\,E_5^2 + \ldots.)^{1/2},$$

where E_1, E_3, etc., are r.m.s. values.

For the equivalent sine wave, we have, in a like manner,

$$e' = E_{max} \sin (x + \alpha);$$
$$de' \div dx = E_{max} \cos (x + \alpha);$$
$$\text{r.m.s.}\ (de' \div dx) = E = (E_1^2 + E_3^2 + E_5^2 + \ldots)^{1/2}.$$

The differential distortion factor is, accordingly,

$$\delta = \frac{(E_1^2 + 9E_3^2 + 25E_5^2 + \ \ldots)^{1/2}}{(E_1^2 + E^2_3 + E_5^2 + \ \ldots)^{1/2}}$$

In this last equation E_1, E_3, E_5, may be either maximum or r.m.s. values.

It is seen that δ depends only upon the amplitude and the order or frequency of the several harmonic components, being independent of their relative phase positions. δ is unity for a sine wave and is greater than unity for an irregular wave by an amount that increases with the amplitude and order of the harmonics present. In the foregoing discussion, terms for odd harmonics only have been introduced; terms for even harmonics can be introduced in a like manner.

When only one harmonic is present, the variation of δ with the amplitude of the harmonic is shown by the curves in Fig. 4; each curve is drawn for a particular harmonic, the amplitude of which is expressed in terms of the fundamental which is taken as unity. The curves in Fig. 4 for the third, fifth, seventh and ninth harmonics approach the values 3, 5, 7 and 9, respectively, as their amplitudes approach infinity. The variation

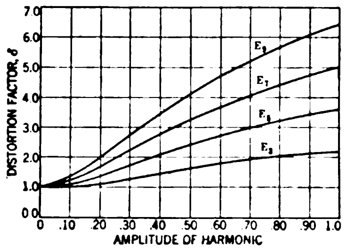

FIG. 4—VARIATION OF DISTORTION FACTOR δ, WITH AMPLITUDE OF HARMONIC

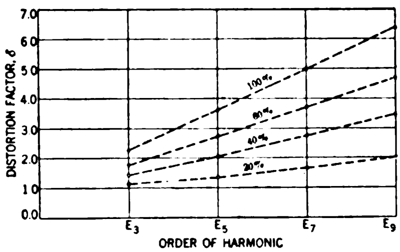

FIG. 5—VARIATION OF DISTORTION FACTOR δ, WITH ORDER OF HARMONIC

of δ with the order of the harmonic is shown in Fig. 5. Figs. 4 and 5 indicate that δ increases in a regular and more or less uniform manner with the frequency and amplitude of any single harmonic present. It is seen that more weight is given to an harmonic of high frequency than to an harmonic of low frequency; whether this is an advantage or otherwise will depend upon the point of view and upon the nature of the case under consideration.

When more than one harmonic is present, the result is not so regular and is not so easy to interpret.

It may be shown that the current flowing into a condenser is directly proportional to δ; that is, $I = \delta\, C\omega E$. It is seen, therefore, that δ is directly proportional to the condenser admittance and inversely proportional to the condenser reactance. Experimental methods for determining δ are thus indicated,

as well as definitions for δ in terms of condenser current, condenser admittance or condenser reactance. Thus, in terms of reactance,

$$\delta = \frac{1}{C\omega} \div \frac{E}{I};$$

which gives the definition,—

The differential distortion factor δ of a distorted voltage wave is the ratio of the reactance ($1 \div C\omega$) of a condenser on a sinusoidal voltage to its reactance (E/I) on the distorted voltage.

Suggestions as to the measurement of differential distortion

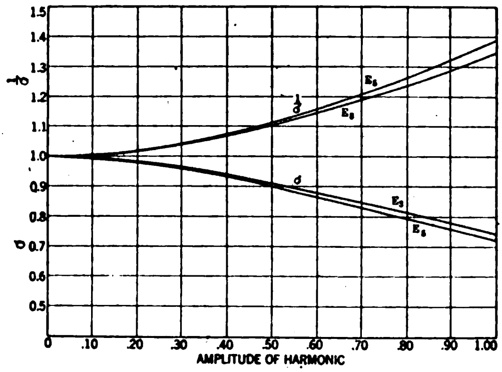

FIG. 6—VARIATION OF DISTORTION FACTOR σ, AND OF $1/\sigma$, WITH AMPLITUDE OF HARMONIC

factor and its definition will be found in a paper[2] by C. M. Davis and in its discussion.

INTEGRAL DISTORTION FACTOR

According to the definition already given, the integral distortion factor has a value

$$\sigma = \text{r.m.s.} \int e dx \div \text{r.m.s.} \int e' dx,$$

where e and e' are the instantaneous values of an irregular wave and its equivalent sine wave, respectively, and x is proportional to time.

2. "A Proposed Wave Shape Standard", TRANSACTIONS, A. I. E. E., p. 775, Vol. XXXII., 1913; discussion, pp. 831-845.

Substituting for e a series of sine terms, as before, and integrating, we have

$$\int edx = -E_{1max}\cos x - \frac{1}{3}E_{3max}\cos 3(x+\theta_3) + \ldots$$

and

$$\text{r.m.s.}\int edx = \left(E_1^2 + \frac{1}{9}E_3^2 + \frac{1}{25}E_5^2 + \quad \ldots\right)^{1/2}.$$

We have, also, for the equivalent sine wave

$$e' = E_{max}\sin(x+\alpha);$$

$$\int e'\,dx = -E_{max}\cos(x+\alpha);$$

$$\text{r.m.s.}\int e'\,dx = E = (E_1^2 + E_3^2 + E_5^2 + \ldots)^{1/2}.$$

The integral distortion factor is, accordingly,

$$\sigma = \frac{\left(E^2_1 + \frac{1}{9}E_3^2 + \frac{1}{25}E_5^2 + \ldots\right)^{1/2}}{(E_1^2 + E_3^2 + E^2_5 + \ldots)^{1/2}}.$$

In this last equation, E_1, E_3, E_5, etc., may be either maximum or r.m.s. values.

It is seen that the factor σ, as well as the factor δ, depends solely upon the amplitude and order of the various harmonics, and is independent of their phase positions. Each factor is unity for a sine wave. Distortion from a sine wave makes σ less than unity, whereas, as has been shown, it makes δ greater than unity. The frequency of an harmonic has less effect on the value σ than on the value of δ.

In Fig. 6 is shown the variation of σ and $1/\sigma$ with the amplitude of the harmonic when the 3rd, or 5th harmonic alone is present. For any harmonic higher than the 5th, the values of σ and $1/\sigma$ are practically the same as for the 5th; thus, for an harmonic equal to 0.60, σ is 0.864 for the 5th, 0.861 for the 7th, 0.86 for the 9th harmonic. (This holds for harmonics of reasonable finite amplitudes, but not when the amplitudes approach infinity; σ then approaches 1/3, 1/5, 1/7 and 1/9 for the 3rd, 5th, 7th and 9th harmonics, respectively.)

Fig. 7, shows how little variation there is of σ and $1/\sigma$ with

the order of the harmonic. It will be recalled that δ on the other hand, (see Fig. 5), varies practically in proportion to the order of the harmonic.

To see what relation there may be between σ and δ, curves are plotted in Fig. 8 showing the values of σ and $1/\sigma$ corresponding to different values of δ. It is seen that there is no simple relation connecting these quantities.

It can be shown that inductive reactance on a distorted voltage wave is inversely proportional to σ; that is

$$I = \sigma E \div L\omega; \qquad \sigma = L\omega \div (E/I).$$

Hence the definition:—

The integral distortion factor σ of a distorted voltage wave

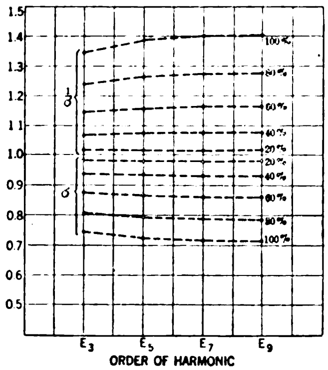

FIG. 7—VARIATION OF DISTORTION FACTOR σ, AND OF $1/\sigma$, WITH ORDER OF HARMONIC

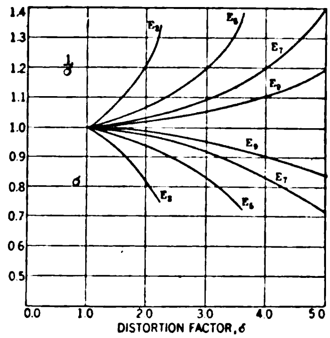

FIG. 8—RELATION BETWEEN σ, $1/\sigma$, AND δ.

is the ratio of the inductive reactance $(L\omega)$ of a coil on a sinusoidal voltage to its reactance on the distorted voltage. The reactance on the distorted wave for most purposes can be considered as being equal to E/I, for a small resistance included with the reactance would introduce but little error, on account of the fact that the effects of resistance and reactance are in quadrature. In precise measurements a correction for resistance might be applied.

COMBINED DISTORTION FACTOR

As there are certain merits in each of the distortion factors δ and σ, and also corresponding disadvantages, according to whether it is desirable to give more or less weight to the higher

harmonics, a combined factor might be found—a useful compromise that would be free from the objections to either one alone. Furthermore, in alternating current calculation, as brought out in the following paper by Mr. Mizushi, certain results depend not upon the factor δ or the factor σ alone, but upon their product $\delta\sigma$, and upon $\Psi = -\cos^{-1}(1 \div \delta\sigma)$. Figs. 9, 10 and 11 are, accordingly, drawn to show the characteristics of these combined factors.

Fig. 9 shows the variation of $\delta\sigma$ and $1/\delta\sigma$ with the amplitude of harmonic.

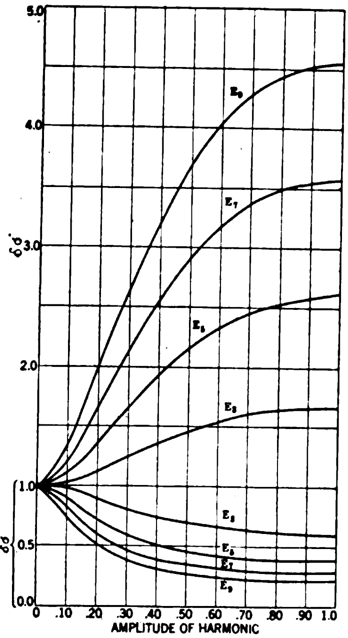

FIG. 9

Fig. 10 shows the systematic variation of $\delta\sigma$ with the order of the harmonic.

Fig. 11 shows the variation of the angle $\Psi = -\cos^{-1}(1 \div \delta\sigma)$ with the amplitude of harmonic.

Aside from the special significance of these combined factors in alternating-current calculation, they may have a general application as a measure of wave distortion.

If an inductive reactance and a capacity reactance are connected in parallel across a circuit, the voltage distortion of which is under consideration, $1 \div \delta\sigma$ is the cosine of the effective phase difference between the currents flowing in them. This suggests possibilities of measurement, should it be found worth while, by some kind of split dynamometer, phasemeter or power factor meter, that would give the value of $\cos \Psi$ and would thus indicate the amount of wave distortion. (Possible error due to resistance in the inductance would have to be taken into consideration). This is a suggestion rather than a recommendation. Possibly some other combination of δ and σ than the one here suggested might prove practicable.

CONCLUSION

It is seen that there are a variety of factors anyone of which may be used as an indication of wave distortion. These factors,

however, differ in their significance and give different weights to various elements or characteristics of wave distortion. Thus, peak factor and form factor (see the paper on form factor immediately preceding) are much affected by the phase relations of the component waves; deviation is less affected, while crest factor, harmonic factor, and the differential and integral distortion factors are not at all affected thereby.

Again, the differential distortion factor gives great weight to the order of an harmonic component, an harmonic of higher frequency having a much greater influence on the value of the factor than an harmonic of lower frequency and the same amplitude, while the integral distortion factor gives little weight to the order of an harmonic, and curve factor and harmonic factor give to it no weight at all.

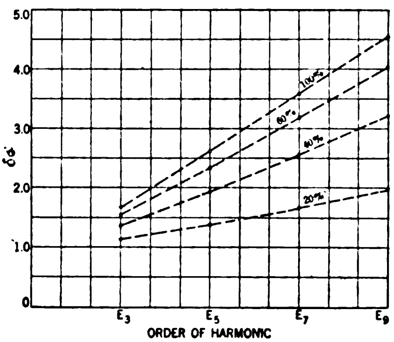

FIG. 10—VARIATION OF $\delta\sigma$ WITH ORDER OF HARMONIC

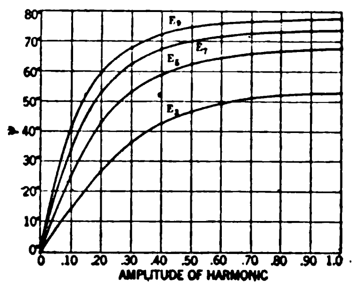

FIG. 11—VARIATION OF $\psi = \cos^{-1} 1/\delta\sigma$ WITH AMPLITUDE OF HARMONIC

Each factor, therefore, with its emphasis on particular characteristics, is suited for its own special use; thus, peak factor and form factor are useful for certain purposes already referred to, differential distortion factor and integral distortion factor are useful for theoretical calculations, etc.

As a general indicator of wave distortion, anyone of several factors would be suitable,—deviation, the curve and harmonic factors, the differential or integral distortion factor, or a combination of these two. Important elements in the selection of a factor are its *availability*, or the readiness with which it may be determined from the available data, experimental or otherwise, and the *definiteness* of its significance. The harmonic factor, or percentage of the combined harmonics, is very defi-

nite in its significance, for it states exactly the components of a wave that are present in addition to the fundamental sine wave and so gives directly the information that is desired for many purposes; but this factor seems hardly available for general use as there is no ready method for determining it. In this respect the distortion factors δ and σ or a combination of the two offer, it is believed, perhaps, the greatest possibilities for usefulness. Their value is enhanced by their specific usefulness in alternating current calculation.

APPENDIX I.

DEFINITIONS AND VALUES OF VARIOUS FACTORS

Factor	Definition	Value
Form factor, f.	$\frac{\text{r.m.s. voltage}}{\text{average voltage}}$	$1.1107 \frac{(E_1^2 + E_3^2 + \ldots)^{1/2}}{E_1 + 1/3\, E_3 \cos 3\, \theta_3 + \ldots}$
Deviation	$\frac{\text{maximum deviation from equivalent sine wave}}{\text{maximum value of equivalent sine wave}}$	
Peak factor	$\frac{\text{maximum voltage}}{\text{r.m.s. voltage}}$	
Harmonic factor, h.	$\frac{\text{r.m.s. of harmonics}}{\text{r.m.s. of fundamental}}$	$\frac{(E_3^2 + E_5^2 + E_7^2 + \ldots)^{1/2}}{E_1}$
Curve factor $(1 + h^2)^{1/2}$	$\frac{\text{r.m.s. voltage}}{\text{r.m.s. of fundamental}}$	$\frac{(E_1^2 + E_3^2 + E_5^2 + E_7^2 + \ldots)^{1/2}}{E_1}$
Differential distortion factor, δ.	$\frac{\text{r.m.s. } (de \div dt)}{\text{r.m.s. } (de' \div dt)^*}$	$\frac{(E_1^2 + (3E_3)^2 + (5E_5)^2 + \ldots)^{1/2}}{(E_1^2 + E_3^2 + E_5^2 +)^{1/2}}$
Integral distortion factor, σ.	$\frac{\text{r.m.s.} \int e\,dt}{\text{r.m.s.} \int e'\,dt}$	$\frac{E_1^2 + (1/3E_3)^2 + (1/5E_5)^2 + \ldots)^{1/2}}{E_1^2 + E_3^2 + E_5^2 + \ldots)^{1/}}$

*NOTE: e' is instantaneous voltage of equivalent sine curve.

APPENDIX II.

Numerical Values of Certain Factors

	δ	σ	$1/\sigma$	$\delta\sigma$	$1/\delta\sigma$	Ψ
E_3 = 10%	1.04	0.996	1.004	1.036	0.971	13°—50′
E_3 = 20%	1.14	0.983	1.017	1.12	0.894	26°—40′
E_3 = 30%	1.29	0.963	1.038	1.24	0.806	36°—20′
E_3 = 40%	1.45	0.937	1.067	1.36	0.736	42°—40′
E_3 = 50%	1.61	0.907	1.102	1.46	0.685	46°—45′
E_3 = 60%	1.76	0.875	1.143	1.54	0.650	49°—30′
E_3 = 70%	1.91	0.841	1.189	1.60	0.625	51°—20′
E_3 = 80%	2.03	0.808	1.238	1.64	0.610	52°—20′
E_3 = 90%	2.14	0.775	1.290	1.66	0.602	53°—00′
E_3 = 100%	2.23	0.745	1.342	1.66	0.602	53°—00′
E_5 = 10%	1.11	0.995	1.005	1.104	0.907	24°—50′
E_5 = 20%	1.39	0.981	1.019	1.363	0.730	43°—10′
E_5 = 30%	1.73	0.960	1.041	1.66	0.602	53°—00′
E_5 = 40%	2.08	0.932	1.073	1.94	0.516	59°—00′
E_5 = 50%	2.41	0.900	1.111	2.17	0.461	62°—30′
E_5 = 60%	2.71	0.864	1.157	2.34	0.428	64°—40′
E_5 = 70%	2.98	0.828	1.208	2.46	0.407	66°—00′
E_5 = 80%	3.22	0.791	1.264	2.54	0.394	66°—50′
E_5 = 90%	3.42	0.755	1.324	2.58	0.388	67°—10′
E_5 = 100%	3.61	0.722	1.385	2.61	0.384	67°—35′
E_7 = 10%	1.21	0.995	1.005	1.20	0.833	33°—30′
E_7 = 20%	1.69	0.981	1.019	1.66	0.602	53°—00′
E_7 = 30%	2.23	0.959	1.043	2.14	0.463	62°—25′
E_7 = 40%	2.76	0.930	1.075	2.56	0.390	67°—00′
E_7 = 50%	3.26	0.897	1.115	2.93	0.342	70°—00′
E_7 = 60%	3.70	0.861	1.161	3.18	0.314	71°—40′
E_7 = 70%	4.10	0.823	1.215	3.37	0.297	72°—40′
E_7 = 80%	4.43	0.786	1.272	3.48	0.287	73°—20′
E_7 = 90%	4.74	0.749	1.335	3.55	0.282	73°—35′
E_7 = 100%	5.00	0.714	1.400	3.57	0.280	73°—45′
E_9 = 10%	1.34	0.995	1.005	1.33	0.752	41°—10′
E_9 = 20%	2.02	0.981	1.019	1.98	0.505	59°—40′
E_9 = 30%	2.76	0.959	1.043	2.65	0.378	67°—50′
E_9 = 40%	3.47	0.930	1.075	3.22	0.310	72°—00′
E_9 = 50%	4.12	0.896	1.116	3.69	0.271	74°—20′
E_9 = 60%	4.70	0.860	1.163	4.04	0.248	75°—40′
E_9 = 70%	5.22	0.820	1.219	4.28	0.234	76°—30′
E_9 = 80%	5.68	0.784	1.275	4.45	0.225	77°—00′
E_9 = 90%	6.06	0.746	1.340	4.52	0.221	77°—10′
E_9 = 100%	6.40	0.712	1.404	4.55	0.220	77°—20′

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(*Subject to final revision for the Transactions.*)

III—AN ANALYTICAL AND GRAPHICAL SOLUTION FOR NON-SINUSOIDAL ALTERNATING CURRENTS

BY F. M. MIZUSHI

ABSTRACT OF PAPER

The solution which is usual in case of sinusoidal currents for series circuits containing *R*, *L* and *C* may be modified by the introduction of current distortion factors δ' and σ' so as to hold for non-sinusoidal currents. The usual solution for parallel circuits may likewise be modified by similar voltage distortion factors, δ and σ.

In Part I. the general analytical solution for series circuits is followed by a corresponding graphical solution and a discussion of special cases. In Part II. the general analytical solution for parallel circuits is likewise followed by a graphical solution and special cases. In both series and in parallel circuits, not only are the effects of *L* and of *C* changed in value by distortion, but these effects are changed, relatively, in phase and are no longer in exact phase opposition as in case of sinusoidal currents and voltages.

The mathematical transformations on which the solutions are based are given in an appendix.

FOR CIRCUITS containing constant resistance *R*, inductance *L* and capacity *C*, the general solution for sinusoidal alternating currents is well known and is in common use. It is desirable to have a corresponding general solution in simple form for non-sinusoidal alternating currents; to develop such a solution, both analytically and graphically is the object of this paper. Certain special cases, to which reference is given later, have been treated by A. Russell, but it is believed that no general solution has been published. The writer is indebted to Dr. F. Bedell, in whose class the investigation originated, for suggestion and assistance in the preparation of this paper, and to various members of the class for their cooperation. The same problem has previously been attacked in this laboratory by B. Arakawa[1]. but in a somewhat different manner.

The treatment is divided into two parts, dealing with series

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1. Vector Representation of Non-Harmonic Alternating Currents, *Physical Review*, p. 409, Nov. 1909.

and parallel circuits, respectively, and in each part the general analytical solution is followed by a graphical solution and a discussion of special cases.

Part I. R, L and C in Series.

Let the voltage and current at any instant be represented by

$$e = E_{1max} \sin (\omega t - \alpha_1) + E_{3max} \sin 3 (\omega t - \alpha_3) + \ldots; \quad (1)$$

$$i = I_{1max} \sin (\omega t - \beta_1) + I_{3max} \sin 3 (\omega t - \beta_3) + \ldots \quad (2)$$

The general relation between e and i for a circuit containing R, L and C in series, is shown by the well known fundamental equation

$$e = Ri + L\frac{di}{dt} + \frac{1}{C}\int idt \quad (3)$$

Let us square each side of this equation and multiply by the operator $\frac{1}{T}\int_0^T dt$. The left hand side of the equation is then equal to the mean square voltage, for

$$\frac{1}{T}\int_0^T e^2 dt = E^2 \quad (4)$$

The right hand side consists of six terms, as given in detail in Appendix I. After some reduction, two of these become zero and the remaining four may be written as follows:

$$E^2 = (RI)^2 + (\delta' L\omega I)^2 + \left(\frac{\sigma' I}{C\omega}\right)^2 - \frac{2L}{C} I^2 \quad (5)$$

or

$$E = \left(R^2 + (\delta' L\omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}\right)^{\frac{1}{2}} I = ZI \quad (6)$$

where Z is the impedance of the circuit, and δ' and σ' are, respec-

tively, the differential and integral distortion factors for current, namely,

$$\delta' = \frac{(I_1^2 + (3\,I_3)^2 + (5\,I_5)^2 + \ldots)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots)^{\frac{1}{2}}} \tag{7}$$

$$\sigma' = \frac{\left(I_1^2 + \left(\frac{I_3}{3}\right)^2 + \left(\frac{I_5}{5}\right)^2 + \ldots\right)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots)^{\frac{1}{2}}} \tag{8}$$

δ' and σ' are *current* distortion factors, marked with a prime to distinguish them from the *voltage* distortion factors (δ and σ) used later. δ and δ' are *differential* distortion factors, while σ and σ' are *integral* distortion factors, the significance of which is discussed in the paper immediately preceding on Distortion Factors by F. Bedell.

Equation (6) gives the value of the impressed voltage at the terminals of a series circuit in terms of the current I and its distortion factors δ' and σ'. Inasmuch as the current has the same value in all parts of a series circuit, it is the current that is the connecting link between the various elements of such a circuit, and it is current distortion rather than voltage distortion that is significant in this case. On this account the solution for a series circuit is restricted in its application. For parallel circuits, the voltage is the common link between the several elements and, as will be shown later, the solution for parallel circuits is therefore in terms of voltage distortion which is a form more suitable for practical applications.

For a non-sinusoidal current, $\delta' > 1$; $\sigma' < 1$.

For a sinusoidal current $\delta' = 1$, $\sigma' = 1$ and equation (6) reduces to the well known form

$$E = I\sqrt{R^2 + \left(L\,\omega - \frac{1}{c\,\omega}\right)^2}.$$

The impedance of a series circuit becomes a minimum for a non-sinusoidal current when $\omega = \sqrt{\sigma' \div \delta'\,L\,C}$, or, for sinusoidal currents, when $\omega = \sqrt{\frac{1}{L\,C}}$

Graphical Solution; R, L and C in Series. Let us use for non-sinusoidal currents, the graphical relation in common use for sinusoidal currents, namely, that reactance and resistance may be

represented by two sides of a right triangle the hypotenuse of which represents the impedance; as in Fig. 1. Thus,

$$Z = \sqrt{R^2 + X^2}$$

From equation (**6**) we also have

$$Z = \sqrt{R^2 + (\delta' L \omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}} \qquad (\mathbf{9})$$

whence

$$X = \sqrt{(\delta' L\omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}} \qquad (\mathbf{10})$$

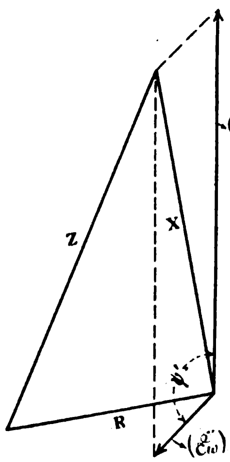

FIG. 1

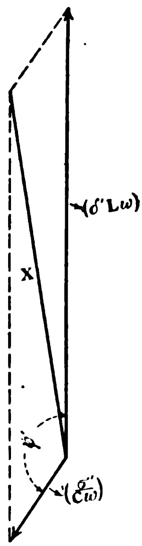

FIG. 2

When δ' and σ' are unity, (**10**) reduces to the well known value for the reactance for sinusoidal currents, $X = L\omega - \frac{1}{C\omega}$; the total reactance is then the arithmetical difference of the inductive reactance and the capacity reactance, which are graphically represented in the same straight line but in opposite directions.

For a non-sinusoidal current, however, the inductive reactance $\delta' L\omega$ and capacity reactance $\frac{\sigma'}{C\omega}$ are no longer in a

straight line, but are laid off as in Fig. 2 with an angle Ψ' between them, where

$$\cos \Psi' = -\frac{1}{\delta' \sigma'}$$

For non-sinusoidal currents, $\Psi' < 180$ deg., for sinusoidal currents, $\delta' = 1$, $\sigma' = 1$, $\Psi' = 180$ deg.

This graphical construction is justified as follows:

From Fig. 1 or Fig. 2, we have, by a well known trigonometrical relation,

$$X = \sqrt{(\delta' L \omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 + 2(\delta' L \omega)\left(\frac{\sigma'}{C\omega}\right) \cos \Psi'}$$

Since $\cos \Psi' = -\frac{1}{\delta' \sigma'}$, this is identical with (**10**) already obtained analytically. $\delta' L \omega$, $\sigma'/C\omega$ and X are in one plane, the relation of which to the plane of Z, X, R is not here determined.

Special Cases for Series Circuit. For L and C, without resistance

$$E = I \sqrt{(\delta' L \omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}} \tag{11}$$

The reactance, as shown in Fig. 2, is the vector sum of $\delta' L \omega$ and $\frac{\sigma'}{C\omega}$, drawn with an angle Ψ' between them. With non-sinusoidal currents, capacity and inductance cannot fully neutralize each other so as to make the total reactance zero, as in the case of sinusoidal currents.

For R and L, alone,

$$E = I \sqrt{R^2 + (\delta' L \omega)^2} \tag{12}$$

For R and C, alone,

$$E = I \sqrt{R^2 + \left(\frac{\sigma'}{C\omega}\right)^2} \tag{13}$$

Figs. 3A and 3B show the reactance component, in quadrature to the resistance component, for these two cases. The solution for these two special cases has been given by A. Russel.[2]

For L alone,

$$E = \delta' L \omega I \tag{14}$$

For C alone,

$$E = \frac{\delta' I}{C\omega} \tag{15}$$

These equations indicate the possibility of determining the current distortion factors δ' and σ' experimentally by measuring the current and the voltage drop around a known inductance or capacity in series with the circuit in question.

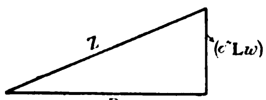

FIG. 3A

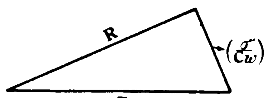

FIG. 3B

PART II. R, L AND C IN PARALLEL

Let the instantaneous values of voltage and current be represented by e and i, as already given in equations (**1**) and (**2**). The general relation between e and i for three circuits in parallel, one circuit containing a conductance $g = \frac{1}{R}$, another L and another C, is given by the general equation,

$$i = ge + C\frac{de}{dt} + \frac{1}{L}\int edt \tag{16}$$

This equation is of the same form as (**3**); it is to be noted however that e and i are interchanged, L and C are interchanged, and $\frac{1}{R}$ or g is written for R. By squaring and multiplying by the operator $\frac{1}{T}\int_0^T dt$, we obtain, in the same manner that equation (**5**) was obtained from equation (**3**), the following solution:

$$I^2 = (gE)^2 + \left(\frac{\sigma E}{L\omega}\right)^2 + (\delta C E \omega)^2 - 2\frac{C}{L}E^2 \tag{17}$$

2. See Alternating Currents, Vol. 1, p. 80.

and

$$I = \left(g^2 + \left(\frac{\sigma}{L\omega}\right)^2 + (\delta\, C\omega)^2 - \frac{2\,C}{L} \right)^{\frac{1}{2}} E = Y\,E \quad \textbf{(18)}$$

where Y is the admittance of the three circuits in parallel, and δ and σ are, respectively, the differential and integral distortion factors for voltage, as discussed in the preceding paper by Dr. Bedell.

$$\delta = \frac{(E_1^2 + (3E_3)^2 + (5E_5)^2 + \ldots)^{\frac{1}{2}}}{(E_1^2 + E_3^2 + E_5^2 + \ldots)^{\frac{1}{2}}} \quad \textbf{(19)}$$

$$\sigma = \frac{\left(E_1^2 + \left(\frac{E_3}{3}\right)^2 + \left(\frac{E_5}{5}\right)^2 + \ldots\right)^{\frac{1}{2}}}{(E_1^2 + E_3^2 + E_5^2 + \ldots)^{\frac{1}{2}}} \quad \textbf{(20)}$$

The admittance Y in equation (**18**) becomes a minimum when $\omega = \sqrt{\sigma \div \delta\, L\, C}$.

For a non-sine wave: $\delta > 1$, $\sigma < 1$. For a sine wave: $\delta = 1$, $\sigma = 1$, and equation (**18**) becomes

$$I = \left[g^2 + \left(\frac{1}{L\omega} - C\omega\right)^2 \right]^{\frac{1}{2}} \times E.$$

Graphical Solution; R, L, and C in Parallel. For a series circuit, use has been made above of the relation $Z = \sqrt{R^2 + X^2}$. For a parallel circuit, use may be made of the corresponding relation

$$Y = \sqrt{g^2 + b^2},$$

the admittance Y being made up of two quadrature components namely, the conductance g, and the susceptance b, as shown in Fig. 4.

From equation (**18**) it is seen that

$$b = \sqrt{\left(\frac{\sigma}{L\omega}\right)^2 + (\delta\; C\omega)^2 - \frac{2\,C}{L}} \quad \textbf{(21)}$$

Figs. 4 and 5 show that the susceptance b is composed of the inductive susceptance $\left(\frac{\sigma}{L\omega}\right)$ and the capacity susceptance

$\delta C\omega$, laid off not in the same straight line (as for sinusoidal currents) but with an angle Ψ between them, where

$$\cos \Psi = -\frac{1}{\sigma\,\delta}. \tag{22}$$

This construction is justified by the fact that, in Figs. 4 and 5,

$$b = \sqrt{\left(\frac{\sigma}{L\omega}\right)^2 + (\delta\, C\omega)^2 + 2\left(\frac{\sigma}{L\omega}\right)(\delta C\omega)\cos\Psi}$$

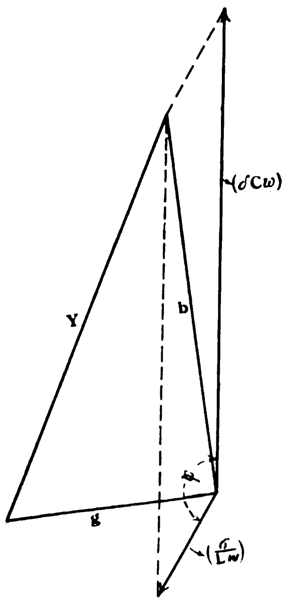

FIG. 4

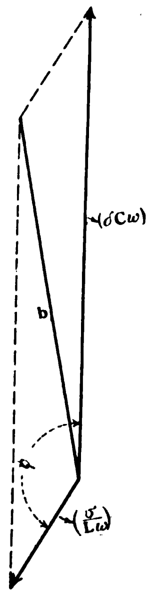

FIG. 5

which becomes identical with (**21**) upon the substitution of $-\dfrac{1}{\sigma\,\delta}$ for $\cos\Psi$.

Special Cases for Parallel Circuits. For L and C in parallel, without resistance,

$$I = \sqrt{\left(\frac{\sigma}{L\omega}\right)^2 + (\delta\, C\omega)^2 - \frac{2C}{L}} \tag{23}$$

The susceptance diagram for this case is shown in Fig. 5. Ψ is the phase difference between the currents in the inductance and capacity and its value indicates the amount of voltage distortion; for a sine wave of voltage, $\Psi = 180°$. This case is partially treated by A. Russell, Vol. I. p. 84.

For R and L, alone, in parallel

$$I = E\sqrt{g^2 + \left(\frac{\sigma}{L\omega}\right)^2} \tag{24}$$

For R and C, alone, in parallel

$$I = E\sqrt{g^2 + (\delta C\omega)^2} \tag{25}$$

The currents through the resistance and reactance, in these two cases, are in quadrature.

For L, alone,

$$I = \frac{\sigma E}{L\omega}\ ;\ \text{or}\ \sigma = L\omega I \div E \tag{26}$$

For C, alone,

$$I = \delta C E\omega\ ;\ \text{or}\ \delta = I \div C E \omega \tag{27}$$

The voltage distortion factors, δ and σ, may thus be determined experimentally by measuring the current taken by a pure inductive reactance or capacity reactance, respectively, when the voltage E is applied to its terminals.

Appendix I. Derivation of Equation (5).

From equation (2) we obtain

$$\frac{di}{dt} = \omega I_{1max} \cos(\omega t - \beta_1) + 3\,\omega I_{3max} \cos 3(\omega t - \beta_3) + \ldots$$

$$\int i\,dt = -\frac{I_{1max}}{\omega}\cos(\omega t - \beta_1) - \frac{I_{3max}}{3\omega}\cos 3(\omega t - \beta_3) \ldots\ldots$$

Squaring (3), operating on it by $\frac{1}{T}\int_0^T dt$, and substituting these values for $\frac{di}{dt}$ and $\int i\,dt$, we have for the right hand side

of the equation the following six terms, designated as (a), (b), (c), (d), (e) and (f). Two of these equal zero; the remaining four, after being reduced and simplified as below, appear in equation (5).

(a) $R^2 \frac{1}{T} \int_0^T i^2\, dt = R^2 I^2$, where I is the r.m.s. value of current.

(b) $$L^2 \frac{1}{T} \int_0^T \left(\frac{di}{dt}\right)^2 dt = L^2 \omega^2 \frac{1}{T} \int_0^T [I_{1max} \cos(\omega t - \beta_1]^2\, dt$$

$$+ L^2\, \omega^2\, 3^2 \frac{1}{T} \int_0^T [I_{3max} \cos 3\,(\omega t - \beta_3)\,]^2\, dt + \ldots$$

$$= L^2 \omega^2\, [\,I_1^2 + (3\,I_3)^2 + (5\,I_5)^2 + \ldots]$$

$$= (\delta'\, L\omega\, I)^2.$$

δ' is the differential distortion factor for current,

$$\delta' = \frac{(I_1^2 + (3\,I_3)^2 + (5\,I_5)^2 + \ldots)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots)^{\frac{1}{2}}}$$

It is to be noted that $\left(\frac{di}{dt}\right)^2$ involves the products of different frequencies, such as $\cos(\omega t - \beta_1) \cos 3\,(\omega t - \beta_3)$, etc., which become zero after being operated on by $\frac{1}{T} \int_0^T dt$.

(c) $$\frac{1}{C^2} \frac{1}{T} \int_0^T (\int i\,dt)^2\, dt = \frac{1}{(C\omega)^2} \frac{1}{T} \int_0^T [\,-I_{1max} \cos(\omega t - \beta_1)\,]^2\, dt$$

$$+ \frac{1}{(3C\omega)^2} \frac{1}{T} \int_0^T [\,-I_{3max} \cos 3\,(\omega t - \beta_3)\,]^2\, dt + \ldots$$

$$= \frac{1}{C^2 \omega^2} \left[I_1^2 + \left(\frac{I_3}{3}\right)^2 + \left(\frac{I_5}{5}\right)^2 + \ldots.\right]$$

$$= \left(\frac{\sigma' I}{C\omega}\right)^2$$

σ' is the integral distortion factor for current,

$$\sigma' = \frac{\left(I_1^2 + \left(\frac{I_3}{3}\right)^2 + \left(\frac{I_5}{5}\right)^2 + \ldots\ldots\right)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots\ldots)^{\frac{1}{2}}}$$

It is to be noted that $(\int idt)^2$, in the same manner as $\left(\frac{di}{dt}\right)^2$, has products of different frequencies, which become zero after being operated on by $\frac{1}{T}\int_0^T dt$.

(d) $2\,RL\frac{1}{T}\int_0^T \left(\frac{idi}{dt}\right) dt$

$$= 2\,R\,L\,I_{1\,max}^2\,\omega\,\frac{1}{T}\int_0^T \sin\,(\omega t - \beta_1)\,\cos\,(\omega t - \beta_1)dt$$

$$+6\,R\,L\omega I_{3\,max}^2\,\frac{1}{T}\int_0^T \sin 3\,(\omega t - \beta_3)\cos 3\,(\omega t - \beta_3)\,dt + \ldots$$

$= 0$

(e) $\frac{2R}{C}\,\frac{1}{T}\int_0^T (i \int idt)\,dt$

$$= -\frac{2\,R\,I_{1\,max}^2}{C\omega}\,\frac{1}{T}\int_0^T \sin\,(\omega t - \beta_1)\cos\,(\omega t - \beta_1)\,dt$$

$$-\frac{2\,RI_3^2}{3C\omega}\,\frac{1}{T}\int \sin 3\,(\omega t - \beta_3)\cos 3\,(\omega t - \beta_3)\,dt - \ldots.$$

$= 0$

$$\text{(f)}\ 2\ \frac{1}{T}\int_0^T \left[\left(L\frac{di}{dt}\right)\left(\frac{\int idt}{C}\right)\right]dt$$

$$= -\frac{2L}{C}\ \frac{1}{T}\int_0^T [\,I_{1max}\,(\cos\omega t - \beta_1)\,]^2\,dt$$

$$-\frac{2L}{C}\ \frac{1}{T}\int_0^T [\,I_{3max}\cos 3\,(\omega t - \beta_3)\,]^2\,dt - \ldots.$$

$$= -\frac{2L}{C}\,(I_1^2 + I_3^2 + I_5^2 + \ldots.) = -\frac{2L}{C}\,I^2$$

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(*Subject to final revision for the Transactions.*)

ELECTRICITY IN GRAIN ELEVATORS

BY H. E. STAFFORD

ABSTRACT OF PAPER

The object of this paper is to show the storage capacity of grain at the terminals of Port Arthur and Fort William, the rated horse power capacity of prime movers, the amount of power used to turn out a given quantity of grain, and the power used by different machines in the process. In addition it gives the details of different plants as regards construction and operation and the method of receiving and shipping grain. It gives a comparison between steam and electrically-driven plants as regards convenience, maintenance, operation and cost. As regards the station end, it shows the lay-out of different stations, the cost of installation, the operation and in some instances, the cost of power. It will be shown in the paper that the cost of handling grain varies, and the reason is fully described. On account of the grain handling season being of short duration, it is the intention of certain companies, to install turbo-generators to overcome the necessity of paying on a peak demand basis. By installing two or more units the operating expenses would be cut to a minimum. With the use of steam power this is impossible.

ELECTRIC power first came into the limelight in this industry in Fort William, in 1902, making this city one of the pioneers in this respect. Electricity was first introduced by the Canadian Pacific Railway, which built a power house operated by steam, for the purpose of electrifying its numerous elevators. This company was the only one using electric power until the advent of the Kaministiqua Power Co., in 1905. The latter company established a power house at the foot of Kakebeka Falls, 18 miles from Fort William, in June 1905, and the first two units of 7000 h.p. capacity were put into operation in December, 1906. A third unit of 7000 h.p. was added in October, 1911, while a fourth unit of 13,000 h.p. was added in August, 1914, making a total of 27,000 h.p. Fig. 1 shows the location of the power house and flumes.

At this point the power is generated at 4000 volts, and stepped up to 25 kv. It is transmitted at this voltage to substations at Port Arthur and Fort William, where it is stepped

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down to 2200 volts. The loss in transmission is approximately 3000 volts.

The substation at Fort William has, at present, three banks of three transformers with a capacity of 5500 kv-a. for each bank. The station at Port Arthur has six transformers of 750 kv-a. each. The connections from power house to station are star-star, star-delta, with grounded neutral. The Corporation of Port Arthur has in addition, a hydroelectric plant at Current River with a total capacity of 2500 kv-a., at 2200 volts, which is used at the heaviest load period to keep down the peak.

Under the names of the different plants will be given a brief description of the various conditions under which they work, obtain power etc. The first two described are the latest built, and will be given in detail.

Western Terminal Elevator

This elevator is a recent type, and is the second in Fort William to purchase a power at 22 kv. The station was completed in August, 1914. The old plant which was built a few years ago is of concrete, with steel and tile cupola, while the tanks are tile. The new house, built in 1914, is of reinforced concrete throughout. The building is built on a foundation of piles driven sixty feet below cut-off. The piles are driven in blue clay, and are capable of standing a stress of between 16 and 20 tons per pile. The grain capacity of the elevator is 2,000,000 bushels. The power contracted for is 700 h.p. The plant is equipped with 56 motors of a total capacity of 1140½ h.p. The motors are used for various purposes some of which are given below.

There are two car-haul motors (one for each track) of 40 h.p. capacity each, capable of hauling 25 cars each. There are six receiving pits and three receiving legs with 22-inch buckets. Each leg is operated by a 75-h.p. motor. The distributing belt conveyers are operated by a 20-h.p. motor each, and the shipping belt conveyers are operated by a 15-h.p. motor each. The loading legs require from 60-h.p. to 75-h.p. motors each.

There are also seven cleaners and three cleaning legs. The cleaner legs take from 15 h.p. to 25 h.p. each, while the cleaners are operated by a 10-h.p. motor each. This plant is equipped with four flax machines, of 10-h.p. capacity each, and two special flax machines of 7½ h.p. each.

Two fans for collecting dust are operated by a 10-h.p. and 15-h.p. motor respectively, and the building is piped with compressed air supplied by a $4\frac{1}{2}$- by 6-in. compresser for cleaning motors.

The station equipment consists of three 250-kv-a. single-phase transformers. The connections are star-delta. The power factor is kept at 90 per cent by two 125-kv-a. condensers. In addition there is a 30-kw. single-phase transformer for lighting purposes. The load factor is about 25 per cent.

Fort William Elevator Co.

This plant was built in 1913 and is of reinforced concrete with brick panelling. The plant, which has a grain capacity of 1,500,000 bu., is operated by both steam and electric power. The boiler capacity (four boilers) is 500 h.p. The engine capacity is 800 h.p. These operate at a steam pressure of 120 lb.

The electric plant consists of a 300-h.p. marine engine direct connected to a 225-kw., 600-volt, 60-cycle, three-phase alternator supplying current to three 100-h.p. motors operating three shipping legs, four 15-h.p. motors operating four, shipping conveyer belts, and one, 20-h.p. motor operating a reversible conveyer belt.

The plant uses 2000 tons of coal per annum at a cost of $4.00 per ton. Below is given the cost of operating the plant for one year.

Coal	$ 8,000.00
Oil	250.00
Waste	32.00
Packing	200.00
Wages	4,000.00
Total per annum	$12,482.00

This makes an average of $34.194 per day. Average load for 365 days = 300 h.p. Average cost per h.p. per annum = $41.606. As this plant also supplies steam for the drier, the actual cost is somewhat below this amount, the actual cost not being known.

The storage capacity of the plant is 48 tanks, each containing 27,000 bu., and 35 intermediate tanks, each containing 7000 bu. There are six receiving pits capable of handling 12 cars or 13,200 bu. per hour. Also nine wheat cleaners and two flax cleaners of 1000 bu. capacity per hour.

The shipping capacity is about 45,000 bu. per hour, and each conveyer belt of 15 h.p. capacity handles 20,000 bu. per hour. Two extra features of this plant are a separater, for separating various grains, and a drying plant. The capacity of the drier is 1000 bu. per hour.

Consolidated Elevator

The total grain capacity of this plant is 1,750,000 bu. Power is delivered at 2200 volts on a contract basis of 700 h.p. The average load is 600 h.p. The total number of motors is 37, ranging from 2 h.p. to 75 h.p., delivering 1007 h.p.

The transformer station consists of 2200 to 600-volt transformers, a synchronous condensor, necessary switch gear, and motors. All other characteristics correspond to the plants previously described.

Canadian Pacific Railway Co.

As before stated, the C. P. R. was the pioneer in the use of electric power for elevator purposes. This plant, which is the only one operated by this company in this city, has a total, grain capacity of 8,000,000 bu. and is the second largest plant in the world. The shipping capacity is 80,000 bu. per hour.

The company discontinued the use of its own power plant, and purchased power from the Kaministiqua Power Co. in 1907. Power is purchased at 2200 volts and stepped to 600 volts at its own transformer station. The transformer capacity is three single-phase, 588-kv-a., or a total of 1764 kv-a. The power factor is maintained at 90 per cent by a 750 kv-a. condenser. The total motor capacity is 2100 h.p., while the average load is 1400 h.p.

Canadian Northern Railway Elevator

This plant is a double one; that is, there are two work houses with the storage tanks between. It has a storage capacity of 9,500,000 bu. and is the largest plant in the world. This plant was first started in 1900, and has been added to at various times, the last addition being made in 1913. Up to that time it was a steam plant throughout, but when the annex was built in 1913, a 200-kv-a. three-phase generator was installed to supply power for it alone.

The total engine capacity of the plant is 2000 h.p. supplied by a 1250-h.p. and a 750-h.p. unit. The coal consumption of

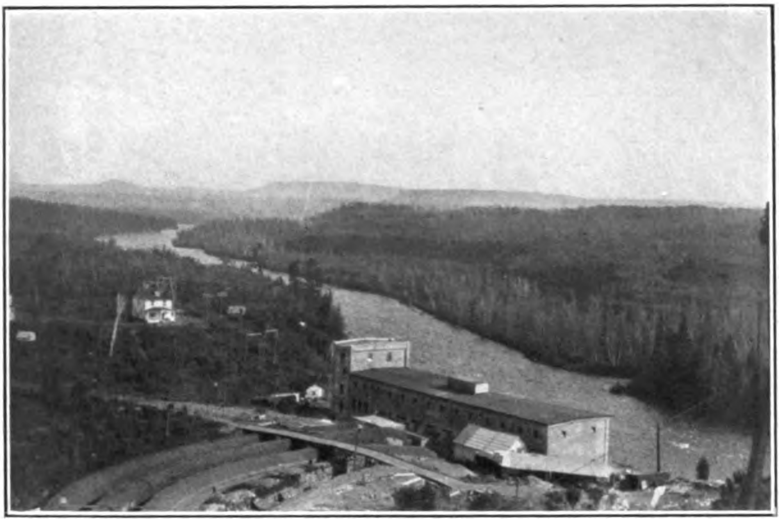


FIG. 1 [STAFFORD]

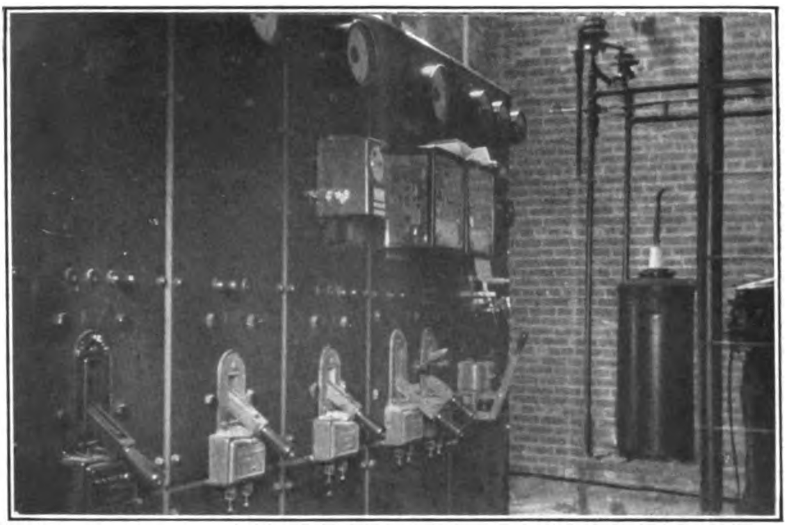


FIG. 2 [STAFFORD]

this plant is 7000 tons per annum, 950 tons of which are used in the driers. The average horse power (steam) is about 1700 The cost of producing power is 0.9 cent per kw-hr. figured on a basis of 3½ lb. of coal per h.p-hour. Statistics of this plant also show that the cost for one year was $22.56 per h.p. for steam power which is an exceedingly low rate.

The average amount of grain handled in one year is 40,000,000 bu.

In Jan. 1914, the elevator was remodeled, necessitating the installation of additional power. As the company was considering using electric power throughout in the near future, it was deemed advisable to erect a substation to accommodate the extra power needed, which could be enlarged as more power was required.

The transformer station is a separate building of brick and tile construction, and was built in 1913. The equipment, which was installed and partly designed by the writer, was put in operation in April 1914. Power is purchased from the City of Port Arthur, at 22 kv. and stepped to 600 volts by three 150-kv-a. transformers connected to a six panel board. The oil switches and busbars are mounted directly on the board, which consists of one main panel, one condenser panel, and four feeders. On the main panel is an ammeter giving the readings from the high-tension side of the transformers, a graphic wattmeter giving the total kilowatts of load, a graphic power factor meter and a maximum demand and integrating wattmeter combined. The voltmeter giving the low-tension readings is mounted on a swing bracket at the end of the board. The four feeders are duplicates and have only an ammeter each, with the necessary switchgear. A detail drawing of connections is shown in Fig. 3. This diagram corresponds to nearly all the low-tension connections in all the elevators. Fig. 2 shows a view of this board and part of the lightning arrester equipment.

A detailed drawing of the synchronous condenser panel is shown in Fig. 4. This consists of three a-c. ammeters, one a-c. voltmeter, one d-c. ammeter, one d-c. voltmeter, and oil switch, two rheostats, synchronizing lamps, switches, plugs and starting controller. The condenser itself is the 200-kv-a. generator mentioned before, and was installed in the station for power factor correction. The condenser is started somewhat differently from the others used in elevator practise (all others are

self-starting) as this machine is started and brought up to speed (900 rev. per min.) by its exciter, which is supplied at 110 volts d-c. by a large generator supplying lights to the elevator. When the machine has reached synchronous speed it is thrown on the line in the usual way and the double-pole, double-throw switch shown in Fig. 4 is thrown to the running position, when the exciter takes care of the condenser, through the generator field rheostat, by which the power factor can be regulated at will. It takes one minute to get the condenser on the line.

The emergency switch mentioned in Fig. 4 is used in case

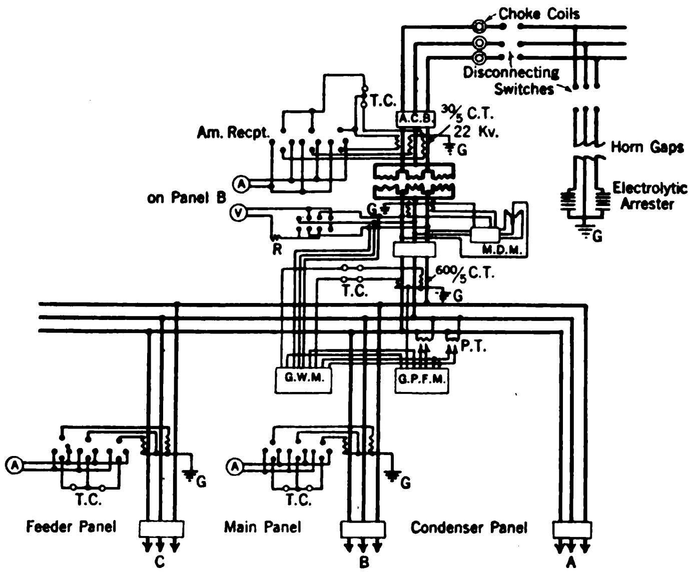


FIG. 3

C.T., current transformer; *P.T.*, potential transformer; *T.C.*, trip coils; *A.C.B.*, automatic circuit breaker; *M.D.M.*, maximum demand meter; *G.W.M.*, graphic wattmeter; *G.P.F.M.*, graphic power factor meter.

the exciter needs repairs. In this case the fields can still be excited from the light generator while such repairs are being made, the condenser of course having to be kept running, as there would be no way of starting it. The short-circuiting switch is for cutting out the controller when the motor is running as an exciter.

The total capacity of the switchgear is about 2000 h.p. while the capacity of the transformers is only 450 kv-a. These of course can be added to at any time. The transformers are delta-delta connected. The station is protected by three elec-

trolytic lightning arresters. The total motor capacity at present is 765 h.p., while the average load is 385 h.p.

Grand Trunk Pacific Elevator

This elevator has a grain capacity of 5,750,000 bu. The motor capacity is 1800 h.p. It was the first in this district to purchase power at 22 kv., having contracted for it in 1909. The substation is large and roomy with a maximum of safety. The building is three stories high. The top floor contains the

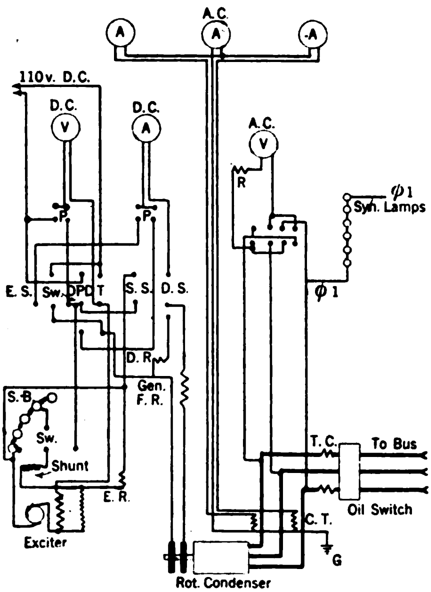


FIG. 4—SYNCHRONOUS CONDENSER PANEL

P., voltmeter-ammeter plug; *S.B.*, starting box; *Gen. F.R.*, generator field rheostat; *D.R.*, discharge resistance; *S.S.*, short circuiting switch; *E.S.*, emergency switch; *D.P. D.T. Sw.*, double pole, double throw switch; *D.S.*, discharge switch; *E.R.*, exciter rheostat; *C.T.*, current transformer; *T.C.*, trip coils.

choke coils, lightning arresters and high tension switchgear. The arresters are the electrolytic type. The second floor contains the light and power transformers. There are three single-phase, 22-kv. to 600-volt transformers with a total capacity of 2025 kv-a., and three lighting transformers of 60 kv-a. each. The ground floor is taken up with the condenser and switchboard. The condenser is self-starting and has a capacity of 750 kv-a. It draws about 800 amperes at starting, and takes about 1½ minutes to get it on the line. The switchgear anp

busses are mounted directly on the board. An extra feature of this station is a fire pump of 500 gallons per min. capacity, driven by a 50-h.p. motor. Fig. 5 shows the elevation of a substation of this type.

The Horn Elevator

This plant, better known as "King's Elevator" was built in 1883 and is the oldest elevator in this part of the country. This elevator, which is an exclusive cleaning and drying plant and is called a "hospital" The grain capacity is 800,000 bu.

The plant is operated by steam, the boiler capacity being 1200 h. p. while the engine capacity is 600 h.p. The excess boiler capacity is used in the drying process. The plant is equipped with seven driers with a total capacity of 20,000 bu. per day, with grain at 8 per cent excess moisture. A thorough description of the drying process comes under the head of "drying," a subject fully described in the latter part of this paper.

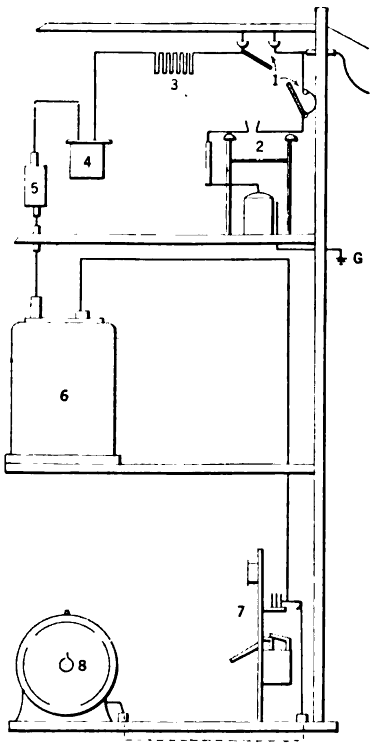


Fig. 5

1—discharge switches; 2—electrolytic lightning arresters; 3—choke coils; 4—high tension oil switch; 5—current transformer; 6—transformer; 7—switch board; 8—condenser.

Ogilvie Milling Co.

This company owns and operates an elevator in connection with its flour mill. The grain capacity of the elevator is 1,250,000 bu., while the capacity of the mill is 3000 bbl. per day.

The rated capacity of motors is 2000 h.p. and the power is purchased on a 1300-h.p. demand basis. Power is delivered to the plant at 2,200 volts and stepped to 600 volts. The milling machinery is connected to a lineshaft driven by an 800-h. p. motor, while the mill cleaning equipment is lineshaft connected to a 250-h.p. motor.

The plants described above cover the field very well, and for

the sake of convenience, the balance of the plants at these terminals, as well as the preceding ones, are given in Table I. This table covers all the data available. It is impossible to obtain all the facts and figures, as most of the companies are very reticent in this respect.

Summary

The power applied to grain elevators, steam and electric, may be summarized as follows:

total h.p.			average h.p.
	Electric power (max. demand)		
$14,412\frac{1}{2}$			8680
	Electric power (flat rate)		
495			475
	Steam power		
4,710			3105
	Combined steam and electric		
800 steam	365 electric	(1165 total)	300

The total capacity of all terminal elevators as shown in Table I is 42,090,000 bu. The total capacity of prime movers is $19,982\frac{1}{2}$ h.p. and the average power is 12,360 h.p. During the season of 1914, the total grain shipments from these terminals was 126,398,622 bushels.

In connection with the types and classes of plants, a little explanation is necessary. There are two types of plants, public and private. These may belong to either of the two classes, as shown in Table I. A public plant is one in which the grain is handled on a percentage basis for any grower or grain company, while the private plant buys the grain outright and disposes of it to suit its needs.

The cost of handling grain is rather hard to figure. A plant may not handle the same amount of grain two years in succession. It may also be stated, that while the characteristics of these elevators as to major details are identical, the conditions under which they operate are at a variance.

It has been shown in Table I, that a certain plant handles 20,000,000 bus. of grain on 1500 tons of coal at $4.00 per ton. Including the operating costs, the cost per bushel over a number of years was shown to be 0.057 cent per bu.

Another plant handled for one year, 30,000,000 bu. of grain on 675 kw. at a maximum demand charge of $10,492.44 on a basis shown at the conclusion of this paper. This brought the cost per bushel down to 0.035 cent per bu.

TABLE I

SQUIRREL-CAGE MOTORS USED IN ALL PLANTS

No.	Name	No. plants	Grain capacity bushels	Motor cap. h. p.	Engine cap. h. p.	Boiler cap. h. p.	Average h.p. elec.	Average h.p. steam	Transformer cap. kv-a.	Condenser cap. kv-a.	Load factor[1]	Power factor
1	Western Terminal	1	2,000,000	1,140½			700		750	250	25%	90%
2	Fort William Elev.	1	1,500,000	365	800	500	100	200				
3	Consolidated Elev.	1	1,750,000	1,007			600		750	200		90
4	Can. Pac. Ry.[6]	1	8,000,000	2,000			1400		1,764	588		90
5	Can. Nor. Ry.[3]	2	9,500,000	765	2000	2000	385	1700	450	200		92
6	Grand Trunk Pac. Ry.	1	5,750,000	1,800			1500		2,025	750		90
7	Horn Elevator	1	800,000		600	1200		600				
8	Ogilvie Milling Co.	1	1,250,000[2]	2,000			1300		1,800			90
9	Grain Growers Co.	3	2,500,000	1,450			900		600	600	45%	90
10	Eastern Terminal	2	1,250,000	1,300			450		525	450	12.15%	90
11	Empire Elevator[5, 6]	1	1,750,000		650	550		300				
12	Thunder Bay Elev.[5, 6]	1	1,500,000		650	550		300				
13	Can. Gov. Elev.	1	3,125,000	2,150			1000		1,300	750		92
14	Smith Davidson Co.	1	750,000	500			125		450	150		92
15	N. M. Paterson Co.[4]	2	175,000	250			250		270			90
16	Parrish & Heimbecker[4]	1	100,000	145			125		150		45%	90
17	Bole Grain Co.[4]	1	20,000	20			20		20			90
18	Muirhead & Co.[4]	1	30,000	30			30		30			90
19	Guy Elev. Co.[4]	1	35,000	50	10	15	50	5	45			90
20	Dwyer Elev. Co.	1	100,000	110			90		120			90
21	Muirhead & Black	1	165,000	100			130		120			90
22	National Elev. Co.	1	40,000	90			100		90			92
	Total	27	42,090,000	15,272½	4710	4815	9255	3105	11,259	3938		

1. Loan factor not available in most cases as no accurate records are kept. 2. Capacity 3000 bbl. per day. 3. Maximum demand charge $27.618. 4. Flat rate charge $27.00 h. p. 5. Cost per bus. 0.057 cent. 6. Cost per ton of coal $4.00.

TABLE I—Continued.

No	Name	H. P. voltage	L. T. voltage	Contract	Coal consumption per annum tons	Average grain handled per annum bushels	Remarks
1	Western Terminal	22,000	600	max. demand			
2	Fort William Elev [6]				2000		
3	Consolidated Elev.	2,200	600	max demand			
4	Can. Pac. Ry.[6]	2,200	600	"			
5	Can. Nor. Ry.[3]	22,000	600	"	7000	40,000,000	
6	Grand Trunk Pac. Ry.	22,000	600	"			
7	Horn Elevator						
8	Ogilvie Milling Co.	2,200	600	"			
9	Grain Growers Co.	2,200	600	"			3 plants supplied by one station
							2 of the plants owned by the Can. Pac. Ry.
10	Eastern Terminal	2,200	600	"			2 plants supplied by one station
							both plants owned by the Can. Pac. Ry.
11	Empire Elevator[5, 6]				1500	20,000,000	actual cost over a number of years as shown later.
12	Thunder Bay Elev.[5, 6]				1500	20,000,000	actual cost over a number of years as shown later.
13	Can. Gov. Elev.	22,000	600	"			
14	Smith Davidson Co.	22,000	600	"			flour mill is to be erected in connection with this plant
15	N. M. Paterson Co.[4]	2,200	600	flat rate			each plant has its own bank of transformers, and one plant has an unloading *spout cap.* 6000 *bus. per hr.* at 50 h.p.
16	Parrish & Heimbecker	2,200	600	"			equipped with oat clipper, cooler, and scalper (see Fig. 7) Cap. of cooler 3600 bus. per hr.
17	Bole Grain Co.[4]	2,200	600	"			equipped with a sacker.
18	Muirhead & Co.[4]	2,200	600	"			
19	Guy Elev. Co[4]	2,200	600	"			equipped with a hot air drier, engine driven.
20	Dwyer Elev. Co.	2,200	600	max. demand			
21	Muirhead & Black	2,200	600	"			max. demand exceeds rated motor capacity.
22	National Elev. Co.	2,200	440	"			max. demand exceeds rated motor capacity.
							equipped with a grinder and sacker.

Another plant handled 500,000 bu. on 100 h.p. flat rate at $25 per h.p. or 0.05 cent per bu.

From Table I, item 5, it will be seen that this plant handled 40,000,000 bu. on 7000 tons of coal, which, with the operating expenses, brought the price to 0.042 cent per bu.

As stated before, this information, while authentic for the period mentioned, can hardly be called an average.

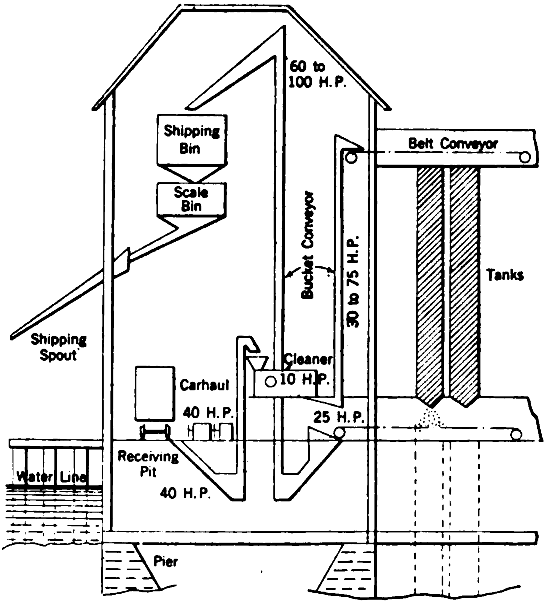


FIG. 6—DIAGRAM OF GRAIN ELEVATOR

HANDLING THE GRAIN IN ELEVATORS

The handling of the grain may be grouped under a number of headings such as,

1. Receiving; car haul, unloading.
2. Cleaning.
3. Conveying; storage tanks.
4. Conveying; hopper conveyer.
5. Weighing; shipping.
6. Drying.

Car Haul. The cars are shunted into the elevator by a yard engine, after which they are moved by a cable drum over the receiving pits. The size of the motors for the car haul depends on the capacity of the elevator and the average number of cars

handled at one unloading. For a train of (25) cars a 40 h.p. motor is used.

The motor starts under no load and the load is gradually thrown on by a friction clutch attached to a cable drum. The strain is sometimes very great as for a train of 25 cars a 40 h.p. motor would exert itself 40 to 60% above rated capacity. As this is only for a few seconds the load as a whole is of little importance.

Unloading. The grain is shovelled from the cars by reverse cable shovels; generally two to a car, each operated by one man. Of course the greater part of the grain leaves the car by gravity as soon as the grain doors are removed, and the shovels are used for the remote corners and floor. It usually takes 30 min. to unload a car containing 1100 bu., 66,000 lb. Each receiving pit has a set of two shovels. The power required to operate two shovels is approximately 7.5 h.p. The load is intermittent and very seldom exceeds the normal capacity of the motor.

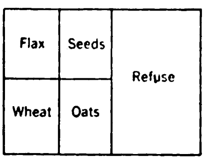


FIG. 7—SCALPER
This consists of five sieves, with a spout leading from each compartment to conveyers.

Cleaning. While the grain does not necessarily go through the cleaning process immediately after it is removed from the cars, this subject will be treated first. From the receiving pits, the grain is carried by bucket conveyers either to the cleaner or storage tanks, as the case may be. The cleaners are located on the first " deck " of the elevator. At the cleaner the grain is separated from the chaff, dirt, etc. The screenings (false grain and others) are transferred to a bin where it is afterward sold for feed. The chaff is drawn by suction into a blower and carried to the boilers direct. The foul seed is taken to a bin where it is afterward disposed of. The power required for the blower is from 15 h.p. for a 2,000,000 bu. plant, to 75 h.p. for a 9,000,000-bu. plant. The load is constant and never exceed the full load rating. The motors for the cleaners range up to 10 h.p. and are never overloaded. The load is practically constant.

Conveying and Storage Tanks. The good grain is taken by a bucket conveyer from the cleaners to the tops of the tanks, where it is dumped on a belt conveyer, to be distributed to the various tanks. The tanks are constructed, as before stated, of steel, tile or concrete. A belt conveyer runs between two sets of tanks and the grain is shunted into the proper tank by means of a " dumper." This dumper consists of a set of rolls, between

which the belt passes, on the same principle as a belt tightener. By closing the dumper the grain is diverted to a chute and then into the tank. The dumper is mounted on rails and is generally moved by hand.

The bucket conveyers require from 50 to 75 h.p. motor capacity, according to the height of the conveyer and the size of the buckets. These motors start under light load, but as soon as the grain starts the motor is loaded to its normal capacity. The belt conveyers probably have the heaviest conditions to work under, having to start under great stress, sometimes double their rated motor capacity, and in many instances the auto-starters are of no use whatever, the handle having to be thrown to the running position to start. It is not an uncommon occurrence for a 15-h.p. motor to blow a 100 ampere fuse, or five times normal load. The load is also intermittent owing to opening and closing of the hoppers, necessary in mixing grades of grain.

In warm weather these motors work at about 75 per cent full capacity, while in cold weather they work as high as 20 per cent above rated capacity, due to the effect of the temperature on shafting, journals, belting etc. In connection with these motors, the question might be asked, "why are not larger motors used?" In the first place the extra cost is to be considered, while in the second place the season for grain handling is generally from the opening of navigation on the Great Lakes until the closing, that is from the 15th of April until the 5th of Dec., or in temperate weather. The motor capacity for belt conveyers is anywhere from 15 h.p. to 50 h.p. depending on the length of the belt. These belts travel at about 650 feet per minute.

Conveying; *Hopper Conveyer*. From the tanks the grain is directed through a hopper in the bottom of the tank to another belt conveyer, where it is carried out of a tunnel under the tanks, to a bucket conveyer, where it is carried to the garner bins.

Weighing and Shipping. From the garner the grain goes into the shipping bin, mounted on scales and situated directly beneath it. After it is weighed, it goes to the shipping spout and thence to the hold of the vessel. The capacity of the scale is 60,000 lb.

Drying. All grain that is damp has to be dried before shipment. No matter how smutty, damp or dirty it is, it is dried and sold to the miller in that state. The elevator companies

used to wash the grain, but it was an expensive operation, considering they got no more for it. The washing bleached it and the value decreased accordingly. Now the mills wash the grain and gage the amount of moisture necessary in the milling process. The defective grain is therefore taken direct to the driers and treated. The drier is a bin generally containing 500 bu. of grain, fitted with vertical sieves and an air chamber, as shown in Fig. 8.

The air chamber is in the center surrounded by the sieves. There is a blank space between each sieve as shown in the cut, and the air circulates in the direction of the arrows. Connected to the drier by an air duct, is a 60-in. fan running at 250 rev. per min. There are two types of driers; hot and cold. The

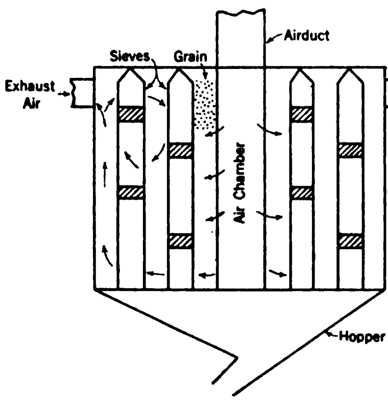


FIG. 8A

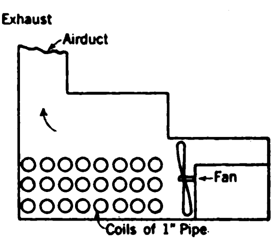


FIG. 8B

heat is generated by steam. Each heater is made up of 6000 feet of one-inch pipe, and the heat is kept at a temperature of 80 deg. cent. A cold air drier is also operated by a fan, taking a good deal longer than the hot air drier. From the driers the grain is taken to the storage tanks.

Period of Shipping. The grain starts to move as soon as navigation opens and continues rather brisk until the bulk of the grain in storage, in the elevators and cars is shipped. This generally takes until the middle of June. The months of July August and part of September are slack; and the time is taken advantage of to make repairs, in readiness for the fall rush. This generally starts in the latter part of September (crop conditions govern this) and continues to the end of navigation. This is the busiest season of the year and the peak is established

during this period. It is during this time that elevator companies get the best advantage of the maximum demand, as they run full 24 hours. As was before stated, navigation virtually closes, midnight December 5th, as the insurance runs out at that time; but a large number of vessel owners carry their own insurance and continue carrying grain until the canals freeze up.

Conclusion

The day load of an elevator is irregular, especially when the process of unloading cars and loading boats is in progress. Fig. 9 shows a typical day load.

The night load on the other hand is practically constant, and is the period taken advantage of. During the night there is very little loading or unloading, and the work done is principally

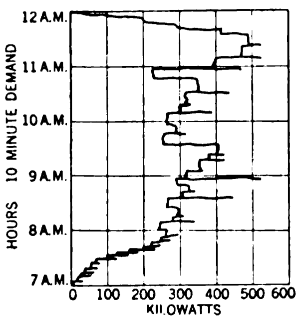


Fig. 9—Typical Day Load
First 5 Hours

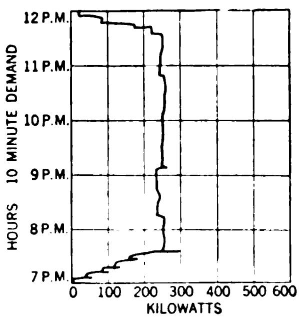


Fig. 10—Typical Night Load
First 5 Hours

cleaning and conveying, the grain traveling in a continual stream. Fig. 10 shows a typical night load.

In Fort William the power factor is maintained at 90 per cent while in Port Arthur it is 92 per cent.

All the induction motors are squirrel cage type, "protected and self ventilating." The motors are all protected by fuses and in most cases have a no-voltage release on the auto-starter. As a general rule the motor is either connected to its load by chain or rope drive; a few are belt connected, while a few are geared. The trouble from break-downs and burn-outs, is almost negligible. With the use of vacuum cleaners and compressed air, and the proper care, probably not more than five burn-outs occur in all the plants in one season. The maintenance charges are very small as these plants seldom employ more than two

operators each. The operators as a general rule receive $125.00, and $90.00 per month respectively.

Cost Data of Stations

The cost per kv-a. for the average 22-kv. station, including buildings transformers, synchronous condensers, high- and low-tension apparatus, is from $37.777 (the lowest) to $42.75 per kv-a.

The cost for a 2200-volt station is from $35.65 to 39.72 per kv-a.

Power Costs

As before stated the flat rate charges are $25.00 per h.p., while the maximum demand is figured on the following basis.

Max. demand in kw		280 kw.	
Transformer losses on max. demand		5½ kw.	
Total kw		285½ kw.	
285½ kw........383 h.p.			
Kw-hr. consumption		28140 kw-hr.	
1st 50 hrs......285½	50	14,275 kw-hr.	
2nd 50 hr.......285½	50	14,275 kw-hr.	
Total		28,550 kw-hr.	
Kw-hr. consumption		28,140 kw-hr.	
Excess		410 kw-hr.	
383 h.p. at $1 per h.p. per month			$383.00
1st 50 hr......14,275	1.3 cents		189.85
2nd 50 hr.......14,275	1 cent		142.75
Excess......... 410	0.1 cent		.41
Total			$716.01
Discount 10 per cent			71.60
Charges per month for 280 kw			$644.41

This gives a rate of $27.618 per kw. per annum, but as this bill was the first rendered and the average load per annum of 40 per cent lower, it would be very misleading to quote any figure on the actual cost per kw. per annum.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

(*Subject to final revision for the Transactions.*)

FIELDS OF MOTOR APPLICATION

BY DAVID B. RUSHMORE

ABSTRACT OF PAPER

This paper is to serve as an introduction to a discussion on the subject of Fields of Motor Application. An industry is defined from an economic standpoint and a list of the principal industries is given. The special points of interest in an industry are given and these are expanded to cover most of the items which would be of interest in investigating an industry from the standpoint of the application of electric motors.

THE NATURAL development of a country takes place through the successive activities of exploration, hunting and fishing, lumbering, mining, agriculture and manufacturing.

Manufacturing is defined by the Century dictionary as "The operation of making goods or wares of any kind; the production of articles for use from raw or prepared materials by giving to these materials new forms, qualities, properties or combinations, whether by hand labor or machinery."

Broadly speaking, the world's activities consist of the production, transportation, distribution and consumption of the necessities of life which, in general, consist of food, clothing and shelter. This may be likened to the generation, transmission, distribution and utilization of electric energy.

Raw materials, in general, consist of matter and stored energy in various forms of fuel. Most industries can be classified under the three general headings of food, clothing and construction. A somewhat more general classification is as follows:

Stone, clay and glass products.
Metals, machinery and conveyances.
Wood manufacturings.
Furs, leather and rubber goods.
Chemicals, oils and paints.
Printing, and paper goods.
Textiles.
Clothing, millinery, laundry.

Manuscript of this paper was received April 30, 1915.

Food, liquors and tobacco.

Water, light and power.

The various industries of the United States and some statistical information pertaining thereto are included in the following tables taken from the latest published Census Reports:

MANUFACTURES IN THE UNITED STATES.

(From Census Bureau's Summary for 1909, issued April, 1912.)

Statement of the general results of the Thirteenth United States Census of Manufactures.

SUMMARY FOR THE UNITED STATES FOR 1909.*

	Census.		Per Cent of Increase, 1904to1909
	1909	1904	
Number of establishments	268,491	216,180	24.2
Persons engaged in manufactures	7,678,578	6,213,612	23.6
Proprietors and firm members	273,265	225,673	21.1
Salaried employes	790,267	519,556	52.1
Wage-earners (average number)	6,615,046	5,468,383	21.0
Primary horse power	18,680,776	13,487,707	38.5
Capital	18,428,270,000	12,675,581,000	45.4
Expenses	18,453,080,000	13,138,260,000	40.5
Services	4,365,613,000	$3,184,884,000	37.1
Salaries	$938,575,000	$ 574,439,000	63.4
Wages	$3,427,038,000	$2,610,445,000	31.3
Materials	12,141,791,000	$8,500,208,000	42.8
Miscellaneous	$1,945,676,000	$1,453,168,000	33.9
Value of products	20,672,052,000	14,793,903,000	39.7
Value added by manufacture (value of products less cost of materials)	$8,530,261,000	$6,293,695,000	35.5

*Not including Alaska, Hawaii or Porto Rico.

Manufacturing industries are of interest from the standpoint of economics, finance and investment, labor, tariff, power consumption, etc.

Points of Interest in an Industry

All industries are identified by the

Finished Product, which is made from

Raw Materials by a

Manufacturing Process with an

Equipment which is driven by

Power and supplied with

Labor in a

Factory involving

Costs and other features of interest; some of which are

Transportation, *Market*, *Competition*, *Financial Aspect*, *History*, etc.

MANUFACTURES BY INDUSTRIES.

Industries.	Average Number of Wage-Earners.	Value of Products	Value Added by Manufacture	Per Cent Increase in Ten Years (a)	(b)
Slaughtering and packing	89,728	$1,370,568,000	$168,740,000	29.5	73.8
Foundries and machine shops	531,011	1,228,475,000	688,464,000	24.4	53.9
Lumber and timber	695,019	1,156,129,000	648,011,000	36.6	51.9
Iron and steel, steel works	240,076	985,723,000	328,222,000	31.0	65.1
Flour and grist mills	39,453	883,584,000	116,008,000	22.4	76.2
Printing and publishing	258,434	737,876,000	536,101,000	32.4	86.7
Cotton goods	378,880	628,392,000	257,383,000	25.1	85.3
Clothing, men's	239,696	568,077,000	270,562,000	52.1	75.4
Boots and shoes	198,297	512,798,000	180,060,000	31.1	76.8
Wollen, worsted and felt goods	168,722	435,979,000	153,101,000	29.1	75.2
Tobacco	166,810	416,695,000	239,509,000	25.9	58.0
Car shops	282,174	405,601,000	206,188,000	62.5	86.0
Bread and bakeries	100,216	396,865,000	158,831,000	66.5	126.3
Iron and steel, blast furnaces	38,429	391,429,000	70,791,000	†2.1	89.3
Clothing, women's	153,743	384,752,000	175,964,000	83.6	141.5
Copper, smelting and refining	15,628	378,806,000	45,274,000	38.0	129.4
Liquors, malt	54,579	374,730,000	278,134,000	38.3	58.2
Leather	62,202	327,874,000	79,595,000	19.4	60.7
Sugar and molasses not inc.beet	13,526	279,249,000	31,666,000	†41.3	16.5
Butter, cheese and milk	18,431	274,558,000	39,012,000	44.0	109.9
Paper and wood pulp	89,492	267,657,000	102,215,000	53.0	110.2
Automobiles	75,721	249,202,000	117,556,000	3278.9	5148.6
Furniture	128,452	239,887,000	131,112,000	41.8	83.6
Petroleum refining	13,929	236,998,000	37,725,000	14.2	91.2
Electrical machinery	87,256	221,309,000	112,743,000	107.7	139.4
Liquors, distilled	6,430	204,699,000	168,722,000	72.8	111.5
Hosiery and knit goods	129,275	200,144,000	89,903,000	54.5	108.8
Copper, tin and sheet iron	73,615	199,824,000	87,242,000	92.1	155.0
Silk and silk goods	99,037	196,912,000	89,145,000	51.4	83.6
Lead, smelting and refining	7,424	167,406,000	15,443,000	†10.8	4.6
Gas, illuminating and heating	37,215	166,814,000	114,386,000	65.7	120.3
Carriages and wagons	69,928	159,893,000	77,942,000	†5.3	16.6
Canning and preserving	59,968	157,101,000	55,278,000	5.2	58.2
Brass and bronze	40,618	149,989,000	50,761,000	49.5	69.2
Oil, cottonseed	17,071	147,868,000	28,035,000	55.1	151.8
Agricultural implements	50,551	146,329,000	86,022,000	8.5	44.6
Patent medicines	22,895	141,942,000	91,566,000	20.3	59.9
Confectionery	44,638	134,796,000	53,645,000	66.2	122.3
Paint and varnish	14,240	124,889,000	45,873,000	46.8	79.5
Cars, steam railroad	43,086	123,730,000	44,977,000	28.8	36.7
Chemicals	23,714	117,689,000	53,567,000	24.7	87.6
Marble and stone work	65,603	113,093,000	75,696,000	57.4	77.6
Leather goods	34,907	104,719,000	44,692,000	19.2	73.3
All other industries	1,634,927	4,561,002,000	2,084,399,000	46.9	100.7
All industries, total	6,615,046	$20,672,052,000	$8,530,261,000	40.4	81.2

*In the year 1909. (*a*) Increase in average number of wage-earners, 1899-1909. (*b*) Increase in value of products, 1899-1909. †Decrease.

In the above table the industries are arranged in the order of their gross value of product. Some of the industries which hold a very high rank in gross value of products rank comparatively low in the average number of wage-earners employed and in the value added by manufacture. Where this is the case it indicates that the cost of materials represents a large proportion of the total value of products, and that therefore the value added by manufacture, of which wages constitute usually the largest item, is not commensurate with the total value of products.

In investigating or describing the application of electricity to various industries, the following subjects form a tentative and necessarily incomplete list of the points of interest:

FINISHED PRODUCT

Description, Complete, Detailed, Condensed Composition, Chemistry.
Uses of Product.
Historical Sketch.
Seasonal Production or Consumption, Operation of Factory. To be sold for consumption or to pass through further manufacturing processes.
Ability to undergo Storage.
Limitation regarding time of shipment and consumption as related to manufacturing, Dairy products, fruit, etc.
Ability to withstand transportation.
Conditions of boxing and other preparations for shipment.
Factors or conditions which injure product.
Quality of product, Affected by what factors?
Size factor, per unit or per pound.
Weight factor, Weight of shipping unit, also per cu. ft., etc., also per unit.
Shipping by mail, express, freight; rates.
Preparation for market.
Specifications to be met.
Tests.
Grades and characteristics.
Reputation, Brands, Trade Marks, etc.
Substitutes.
Product is sometimes, Labor or Service.
Stock.
Cost Analysis, Also diagram of general cost plan.
Price fluctuation over term of years.
Production by countries and localities over term of years.
Consumption by countries, localities, trades, etc.
By-products.
Waste, Refuse, Scrap, Unsaleable Residue.
Exports and Imports.

RAW MATERIAL

Source, Geographical, Manufactured.
Classification, Grades, etc.

Export and Import.
Production, Country, Seasonal.
Control or Open Market.
Natural or Manufactured Products.
Limitation to Supply.
Substitutes.
Percentage Loss Necessary, Raw Material to Finished Product.
Specifications and Tests, Inspection, Varieties, Grades, Impurities.
Purchasing.
Storage.
Stock to be kept on hand.
Per cent of Cost of Product.
Adulterants Used.
Indications of Purity.
Undesirable Ingredients.
Ownership of Supply.
Preliminary Treatment.
Danger to which it is exposed, Depreciation with Age, Moisture, Heat, Cold. Vibration, etc.
Seasonal Production.
Price Fluctuations over Term of Years.
Transportation, Costs and Ability to Withstand.

Manufacturing Process

Characteristics of Raw Material as received.
Preliminary Treatment Necessary.
Description of General and Detailed Steps in Process by which the Raw Material is Converted into Finished Product.
Particular Requirements of Process as regards Time, Temperature, Pressure, Power, Speeds.
Critical Points in Process, Method of Determination, Precautions.
Diagram of Flow of Material through Process.
Possible points for improvements.
Alternative processes possible with relative advantages and Disadvantages of each.
Mixtures of ingredients to be used with specifications and the results of variation of quantity and quality.
Result of stoppage of any part or all of plant.
Use of steam for manufacturing purposes.
Use of Water, Gas, Oil and Coal for manufacturing purposes other than power.

Equipment and Power

List of steps in Process and Description of Machine used for each step.

List of Manufacturers of each kind of Machine.

Load Curves or Duty Cycle of each Machine.

Conditions, of Starting, Accelerating, Running, Braking, Reversing, etc.

All Factors involved in the Motor Application such as Atmospheric Conditions, of Dust, Injurious or Inflammable Gases; exposure to outside heat, vibration, noise, safety precautions, illuminations, accessibility of repairs, use of flywheels, protection for belts, etc.; method of mounting, method of drive, ventilation, shaft extensions, lubrications, clutches, oil drainage, type of frame, methods of adjustment and alignment, etc, etc.

Photographs and Drawings of Machines showing mounting of Motor and Control wherever possible.

Points determining Type and Capacity of Motor.

Points determining Type and Capacity of Control.

Distributing System.

Generating System.

Methods of Measuring Power Consumption.

Important Points in Power Contract.

Cost of Manufactured or Purchased Power.

Load Curve of Plant as a whole.

Factory

1. Location of factories manufacturing product with reasons for such location and output of each.
2. Ground plan of factory showing generating plant or substation, Buildings, Location of machines, Path of flow of materials, etc.
3. Elevation of principal buildings where this will give desirable information.
4. Diagram of electric distributing circuits.
5. Storage facilities for raw material and product.
6. Methods of illumination.
7. Safety precautions.

Labor

1. Location of factory.
2. Existence of special class of labor especially skilled in industry.
3. Curve of wages over term of years.

4. Relative labor efficiency.
5. Relative costs of operations by hand labor and electrically driven machinery.
6. General intelligence of labor and care of apparatus which may be expected.

Costs

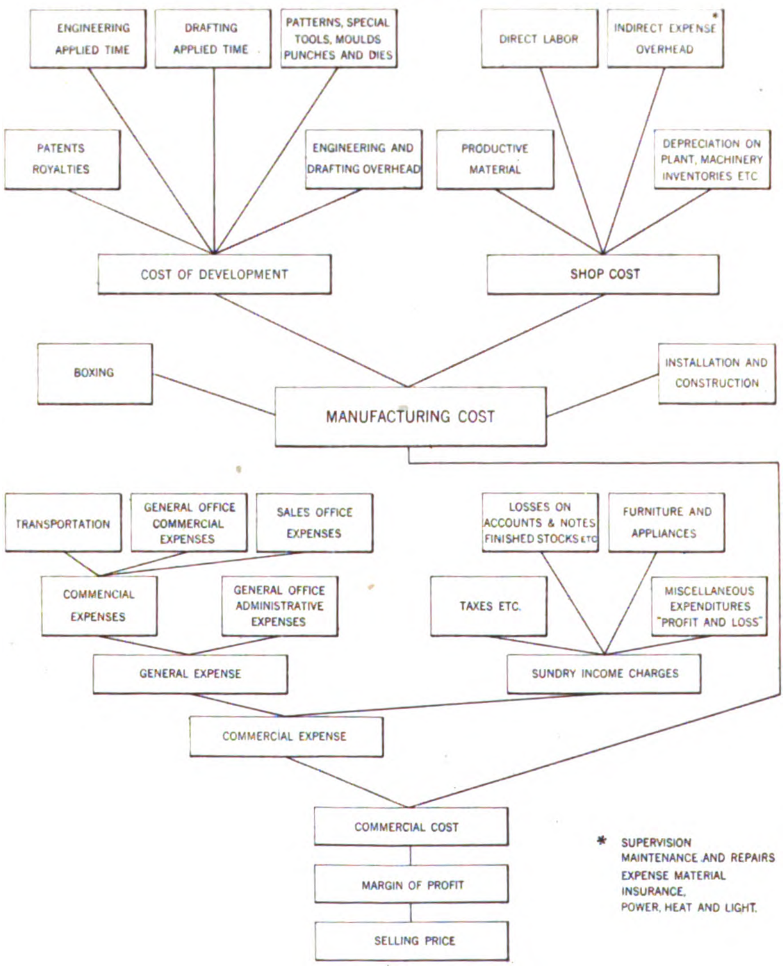
1. Diagram and detailed description of methods of estimating cost of product and of factors involved.
2. Tabulation of cost factors in per cent of the whole, showing the relative importance of the items of power, labor and materials.
3. Indicate directions in which effort can be most advantageously employed toward saving in cost and improvement in quality of product.
4. Outline in detail economic value of electric drive.

As a factor of greater efficiency and saving in power cost.
As allowing the purchase of power and therefore the reduction of capital investment.
Increased production for a given equipment.
Improvement in the quality of product due to constant speed.
The possibility of centralizing the power supply.
Simplicity in power transmission and distribution.
Convenience in location of machinery with reference to production rather than to power transmission system.
Ease of making changes.
Reduction of friction losses.
Improved cleanliness and better light and safety due to absence of large number of belts.
Greater reliability in operation.
Possibility of selection of suitable motors.
Ease of control.
Possibility of remote and automatic control.
Possibility of recording power consumption and of investigating the operation of machinery.
Time economy and possibility of sectional operation of shop or factory, making the power consumption approximately proportional to the work.

The following diagram of costs is impersonal and does not represent the practise of any one particular company. The proper method of estimating costs is, however, so little understood by manufacturing concerns that but few include all of the items which really make up a part of the total expense involved in the production of a product.

In order to appreciate the economic part played by the electric motor in manufacturing industries it is necessary to have the detailed cost sheet. The valuation of the various factors of advantages of the electric motor application, other than

ITEMS IN THE COST OF A FINISHED PRODUCT



those involved in the direct reduction of power cost, is a treatment so special as to necessitate its separate statement for each industry.

The object of this paper is to give a brief outline of the points

of interest in industry and to point out the factors involved in the application of electric motors to manufacturing purposes. It is intended to serve as an introduction to a discussion which will bring out the points of interest in the various industries in which the electric motor has been applied.

This paper is the fourth and last part of a treatment of Industrial Power Applications, the other parts of which have been Electric Motors, Electric Controllers, and the Factors Involved in Motor Application, which were presented respectively at the New York, Pittsburgh and Cleveland Meetings.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., July 2, 1915.

AN INVESTIGATION OF DIELECTIC LOSSES WITH THE CATHODE RAY TUBE

BY JOHN P. MINTON

Abstract of Paper

This paper discusses the theory of the cathode ray tube wattmeter and shows how it can be used to determine directly the power factors of insulations. The current and voltage are measured independently so that the dielectric losses in insulation can be calculated. Such measurements can be made up to the breakdown voltage of the material being tested.

The development of the cathode ray tube and its auxiliary apparatus is discussed.

Measurements of dielectric losses, power factors, and currents, for varnished cloths and oil-treated pressboard are given. The measurements have been made at 60 cycles at different voltages, temperatures, and moisture contents in the case of pressboard. Curves are given showing the losses, power factors, and currents plotted against voltage, temperature, and per cent absorbed moisture.

Empirical equations are derived for all the curves. It is shown that watt losses may vary from the 1.32 to the 2.52 power of the voltage. The losses and currents can be expressed by an equation of the form; $K_1 + K_2 Y^n$, where Y may be temperature in deg. cent. or per cent absorbed moisture. The same form of equation holds for the power factors up to about 85 per cent. The equations given show that the exponent n may vary from about four to seven, depending on the conditions of the tests and on the nature of the insulations.

The large and harmful effects of moisture are clearly shown by the results, and the weakening effects due to high temperature are of much importance.

Introduction

Careful study of insulating materials is becoming more and more important. Formerly, if an insulating material was not satisfactory, it was discarded and a new one substituted. In this way considerable progress was made. However, as the number of possible insulators became less, it became more evident that it was necessary to study the electrical properties of these with the hope of improving them. Today, this tendency toward a careful study of various dielectrics is quite prominent, and it is certain to become much more noticeable in the near future. Certainly we are now looking toward improvement in all kinds of insulations, and in seeking

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this improvement, the most careful and thorough investigations cannot be over-emphasized.

Heretofore, the electrical tests made on insulation have largely been voltage tests, capacity and resistance measurements. The voltage tests are important because insulation must be able to withstand continued application of voltage and sudden voltage increases such as occur in transient phenomena. These tests reveal very little about the insulation because either it does or does not withstand them. This is really about all they do tell us, because if the insulation is broken down, no further test can be made on it, and if it is not broken down, we can say nothing regarding its value as compared with other insulation which fails to break down under test. Capacity measurements are only made at low voltages and not at anything like normal operating voltages. Such measurements are important in helping one to select the proper insulation, but no one would decide to use a certain kind of insulation from consideration of capacity measurements only. These measurements do not tell us enough. In the same way resistance measurements do not tell us enough, and indeed it is difficult to say what the resistance of a piece of insulation is except for direct currents, which at the present time are of much less interest to the engineer than alternating currents.

On account of the inadequacy of the three kinds of electrical measurements mentioned on insulation, the measurement of dielectric losses and power factors of insulations becomes of much importance and of great interest. By means of such measurements, one is able to study a piece of insulation up to almost the breakdown point under a variety of conditions and over and over again. He can continue these measurements until the insulation finally breaks down, and will know what is happening within it up to this point. Such measurements will reveal to us more about insulation than all the three tests referred to above. If scientific progress in insulation engineering is to be made, then measurements of dielectric losses, power factors, and currents will prove most valuable in pointing out ways of advance and in keeping us off wrong paths.

In searching the literature, one at once realizes that very few extended researches have been conducted along the line of dielectric losses. The most notable ones have been carried out in England during the past few years by E. H. Rayner,[1] by C.

1. "High Voltage Tests and Energy Losses in Insulating Materials" E. H. Rayner, *Journal Inst. Elec. Engrs.*, Vol. 49, pp. 3-89, 1912.

C. Paterson, E. H. Rayner, and A. Kinnes[2], and by Fleming and Dyke.[3] The latter made use of the bridge method, while the two former made use of the electrostatic wattmeter. Both of these methods have the disadvantage of being limited in the voltage at which they can be used, and the electrostatic wattmeter is a very troublesome instrument with which to work. The whole reason why such measurements have not been carried out on a large scale before is because one is confronted with the difficulty of securing instruments which will measure small losses at very high voltages. Prof. Ryan first suggested the use of the cathode ray tube for this purpose and showed[4] how it could be used by giving a number of examples of measurements made with it. The development of the *cyclograph*, which is the name given to the cathode ray tube wattmeter was begun in 1911 at the Pittsfield Laboratory, and has been accomplished, so that it is a satisfactory apparatus to measure dielectric losses up to almost any desired voltage, from very small to large losses, and from low to high frequencies, so long as a continuous alternating potential is available. The cyclograph has been in continuous use in this laboratory during the past two years, and a large amount of valuable information has been gained both on cathode ray tubes and on insulation. The application of the cyclograph to this work, its development, some of the results obtained with it, and a study of dielectric losses made possible by its use, are embodied in this paper. Since the writer has had little assistance from current literature, he cannot hope to say the last word, or even avoid making wrong inferences. The results and information set forth in this paper may be considered as opening up a new avenue for insulation research for both the electrical engineer and the scientist.

At this point the writer acknowledges his appreciation of the kind interest taken in this work and the helpful suggestions of Mr. A. McK. Gifford, in charge of the Pittsfield Laboratory, and Mr. C. R. Blanchard, in whose section of the laboratory the work has been done. He is also indebted to Mr. W. C. Slade, of this laboratory, for his willingness to do the necessary

2. "Use of the Electrostatic Method for Measuring Power." C. Paterson, E. H. Rayner, and A. Kinnes. *Journal Inst. Elec. Engrs*, July, 1913, pp. 294-360.

3. "Energy Losses at Telephonic Frequencies." Fleming and Dyke, *Journal Inst. Elec. Engrs.* Vol. 49, p. 323, 1912.

4. *A Power Diagram Indicator*, Harris J. Ryan, A. I. E. E., Vol. 30, pp. 511-535, 1911.

glass-blowing in order that this work could be made possible. To the other men in the laboratory, who have assisted in this work either by suggestions or otherwise, the writer expresses his gratitude.

I. Object of the Investigation

The object of the present investigation was three-fold. First, to show the usefulness of the cathode ray tube in studying the dielectric losses which occur in insulations. Second, to measure dielectric losses, power factors, and currents at different voltages and temperatures in different insulations under various conditions. Third, to obtain a better understanding of the mechanism of dielectric conduction and to obtain empirical laws governing the electrical phenomena occurring in insulation when it is subjected to high voltage stresses. The results which have been attained and the information acquired through this investigation show that this three-fold object, has been accomplished. The results of this work will now be given.

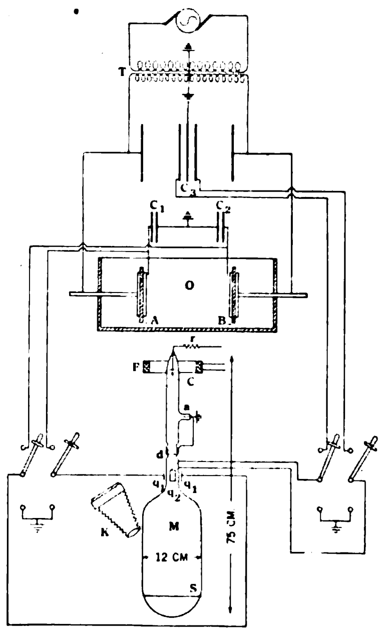

Fig. 1

II. Method of Determining Dielectric Losses

Since the method of determining the dielectric losses with the cyclograph is quite different than that described by Prof. Ryan,[5] it will be necessary to show how the apparatus is used for this purpose. The cathode ray tube, M, is an evacuated glass tube of the dimensions and shape shown in Fig. 1. Under the proper conditions, a direct potential of about 20,000 volts, applied between the cathode C and the grounded anode, A, will cause a stream of cathode rays to originate at the cathode and travel at a very high velocity toward the other end. It is necessary to have C the negative terminal because the cathode

5. *Loc. Cit.* 4.

rays consist of electrons which possess negative charges. A grounded brass diaphragm, d, intercepts all these rays with the exception of those which pass through a round hole about 1/32 in. in diameter in this diaphragm. This small pencil or bundle of rays travels to the lower end of the tube where it strikes the fluorescent screen S. This fluorescent screen is usually made of calcium tungstate (Ca WO_4), or zinc sulphide (ZnS), or some other salt which is strongly fluorescent when subjected to the bombardment of cathode rays. For a fuller discussion of the cathode rays and their properties, the reader is referred to a recent article by the writer[6]. A more complete discussion on the cyclograph will appear in another section, but this will be sufficient to understand the theory of the apparatus.

Theory of the Cyclograph. In order that the fluorescent figure on the screen may be symmetrical with respect to the center, it is necessary in this scheme to use two pieces of similar insulation. These two pieces are represented by A and B and placed between the test terminals in the oil-box, O, as shown in Fig. 1. Suppose now a high-potential sine wave is applied to these test pieces by means of the transformer T, and that it is desired to measure the dielectric loss in them. Fig. 1 shows the diagram of connections to be used. For this purpose, a sine-wave potential, proportional to the voltage across the test terminals in the oil-box is applied to the potential quadrants, q_2, q_2. This potential is obtained from the air potential condenser C_3, as shown in the diagram. It may be represented by:

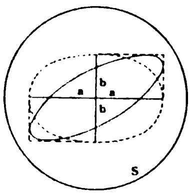

FIG. 2—FIGURES PRODUCED BY THE FLUORESCENT SPOT ON THE SENSITIVE SCREEN S

$$e = e_0 \sin pt \tag{1}$$

This potential produces the deflection of the cathode ray spot on the fluorescent screen S, as shown by bb in Fig. 2. Since the cathode rays possess no appreciable inertia, it follows that this deflection is directly proportional to E, so that

$$b = k_0\, e_0 \sin pt \tag{2}$$

To the current quadrants, $q_1\ q_1$, is applied a potential e_1, proportional to the current passing through the insulation under

6. "Cathode Rays and Their Properties." J. P. Minton, *General Electric Review*, Vol. 18, pp. 118-125, 1915.

test in the oil box. This potential is obtained from the air, current condensers, C_1 and C_2, as shown in Fig. 1. The voltage across an air condenser is directly proportional to the current passing through it. The current that passes through these condensers is that which passes through the insulation under test, and it may be represented by:

$$i = I_0 \sin (pt + \theta) \tag{3}$$

where θ is the angle of lead of the current over the voltage applied to the test terminals. Since i leads e_1 by 90 degrees and since i is proportional to e_1, we have from equation (3):

$$e_1 = k_1 I_0 \cos (pt + \theta) \tag{4}$$

This potential e_1 produces the deflection aa of the cathode ray spot as shown in Fig. 2. The deflection is proportional to e_1, so that

$$a = k I_0 \cos (pt + \theta) \tag{5}$$

Placing $a = x$, $b = y$, and $k_0 e_0 = k_2 E_0$, we have, rewriting equations (5) and (2)

$$x = k I_0 \cos (pt + \theta) \tag{6}$$

and

$$y = k_2 E_0 \sin pt \tag{7}$$

When both of these potentials act on the cathode ray stream simultaneously, an ellipse is formed on the screen, S, by the fluorescent spot, in Fig. 2. The area of this ellipse is given by.

$$A = \int_0^{2\pi} y \, dx \tag{8}$$

Making use of equations (6) and (7), we obtain from equation (8)

$$A = -k k_2 E_0 I_0 \int_0^{2\pi} \sin pt \sin (pt + \theta) \, p \, dt \tag{9}$$

or

$$A = -k k_2 E_0 I_0 \int_0^{2\pi} (\cos \theta \sin^2 pt + \sin \theta \sin pt \cos pt) \, p \, dt \tag{10}$$

Integrating and placing in the limits of integration we obtain.

$$A = -\pi k k_2 E_0 I_0 \cos \theta \tag{11}$$

Placing $-\pi k\ k_2$ = a constant, and replacing the maximum values of E_0 and I_0 by their effective values E and I, we have;

$$A = K\,E\,I \cos\theta \tag{12}$$

Now, E = the voltage applied to the system, I = current passing through the insulation, and $\cos\theta$ = the power factor of the system. Therefore, the area, A, of the ellipse is proportional to the power lost in the insulation and air condensers, C_1 and C_2. Since the loss in the air condensers is negligible, we see that the area of the ellipse is proportional to the dielectric loss in the two pieces of insulation under test. This is the same result obtained by Prof. Ryan by a different line of reasoning. However, the use of the cyclograph in this manner would require calibration under various conditions in order to determine the multiplying factors necessary to reduce the area to units of power. Calibrations are not pleasant things to obtain, and, fortunately, they are not at all necessary. These calibrations are avoided by the use of the cyclograph as a power factor and meter by measuring the currents and voltages independently. These two latter quantities can be determined without trouble and we shall see that the power factors are easily obtained from photographs taken of the fluorescent figure.

Use of the Cyclograph as a Power Factor Meter. Equation (**12**) gives the area of the ellipse when the power factor of the circuit (consisting of the two test pieces and air condensers C_1 and C_2) is equal to $\cos\theta$. If the power factor of the circuit were unity instead of $\cos\theta$, then the area, A_0, of the ellipse would be equal to KEI, and it is represented by the dotted ellipse in Fig. 2. It is evident that

$$\frac{A}{A_0} = \frac{KEI\cos\theta}{KEI} = \cos\theta \tag{13}$$

A can be obtained by measuring the major (a') and minor (b') axes of the actual ellipse formed by the fluorescent spot on the screen, $S_1 \cdot A_0$ can be obtained by measuring a and b, Fig. 2. Hence, $\cos\theta$ can be determined by applying equation (**13**). This makes it evident that it is advisable to make three exposures for each photograph, one of the ellipse, one of the deflection a, and one of the deflection b. However, one exposure, that of the ellipse, would be sufficient to determine $\cos\theta$. These photographs are taken at an angle as indicated

in Fig. 1, but on account of taking the ratio of A to A_0, no errors are introduced in the values obtained for cos θ.

Equation (**13**) gives the value of the power factor of the circuit, but one desires the power factor of the insulation which is being tested. This is obtained from Fig. 3, which is the vector diagram for the circuit consisting of the two test pieces and air condensers C_1 and C_2. The voltage across this circuit is represented by E, and the current passing through it is represented by I leading E by an angle θ. e_1 is the potential drop across the air condenser, and it is at right angles to I. E' is the voltage drop across the insulation, and θ' is the phase angle between I and E'. The power factor of the insulation, therefore, is cos θ', which is the one sought. It can be determined as follows:

$$\sin \alpha = \frac{e_1}{E'} \cos \theta$$

$$\cos \theta' = \cos (\theta - \alpha)$$

From which it follows that:

$$\cos \theta' = \frac{e_1}{E'} \sin \theta \cos \theta + \cos \theta \sqrt{1 - \frac{e_1^2}{E'^2} \cos^2 \theta} \quad \textbf{(14)}$$

Now, $\frac{e_1^2}{E'^2} \cos^2 \theta$ is of such a value that it can be neglected and in doing so, an error not greater than 0.7 per cent will be introduced in the values obtained for cos θ'. Hence equation (**14**) becomes approximately,

$$\cos \theta' = \cos \theta + \frac{e_1}{2E'} \sin 2\,\theta \quad \textbf{(15)}$$

Below we shall see how to determine e_1 and E', and from equation (**13**) we can calculate θ. Hence, by substituting the values for these three quantities in equation (**15**), we obtain the values for cos θ', the power factor of the insulation being tested. The value of the correction term in equation (**15**) is obtained by plotting cos θ vs. $\frac{1}{2}$ sin 2θ. Then, when we know cos θ, we can get values for $\frac{1}{2}$ sin 2θ from the curve. Multiplying these values by e_1 and dividing by E', we obtain the corrections. These corrections amount from about 0 to 10 per cent of cos θ, depending on the conditions of the tests.

Measurement of Current. The current that passes through the insulation also passes through the air condensers C_1 and C_2. Under normal conditions, the current passing through any air condenser is given by

$$I = 2\,\pi\,f\,C\,e_1 \times 10^{-6} \text{ amperes,} \tag{16}$$

where e_1 = potential in volts across the condenser,

C = Capacity in mfds. of the condenser,

f = frequency of the applied potential.

So that this equation can be used to obtain the current passing through the insulation.

The voltage, e_1, across the air condensers has been determined with a 120-volt Kelvin electrostatic voltmeter used either with a shunt or with two auxiliary condensers one connected on each side of the ground between C_1 and C_2 in Fig. 1. In the first case the voltmeter was calibrated to read directly the

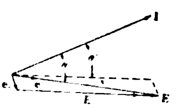

FIG. 3—VECTOR DIAGRAM FOR TESTING CIRCUIT

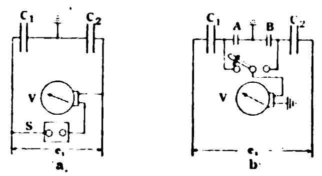

FIG. 4

voltage across the two condensers C_1 and C_2. In the second case, the voltmeter was calibrated to read directly the voltage across these two condensers plus the two auxiliary condensers. The second method has proved much more reliable because one terminal and the metallic case of the electrostatic voltmeter can be grounded, and the auxiliary condensers are sufficiently large to permit the 120-volt Kelvin meter to be connected directly across them. The first scheme is represented in Fig. 4*a* and the second in 4*b*. In 4*b*, the average of the readings across A and B is taken to represent the value of e_1 to be used. e_1 varies from 600 to 3000 volts, depending on the conditions of test. This second method is quite satisfactory, and can always be relied upon to give accurate results. The shunt method is objectionable because it requires a very small capacity for the shunt, and it is affected by disturbing influences, which will not affect the second method in the least. These two auxiliary condensers, A and B, have sections of different capacities and

one section or another can be switched in or out depending on the amount of current passing. They are made of paraffine treated bond paper and each occupies a space 10 in. by 8 in. by 2 in., being firmly constructed so as not to undergo any change in capacity. The loss in these paraffine condensers is less than one part in two or three hundred of the total losses, so that they introduce no appreciable error in the results.

The air capacities, C_1 and C_2, or these in series with the two auxiliary condensers A and B, range from about 0.003 to 0.015 microfarads. This range has been found sufficient for this work on dielectric losses. The frequency of the applied potential is measured without any difficulty. Therefore, the current can be calculated by means of equation (**16**). The current per sq. cm. can be obtained by dividing the total current by the area of the testing terminals; all the current values given in this paper are in milliamperes per sq. cm. The test terminals used were either 20 or 25.4 cm. in diameter, and results obtained with 10-cm. terminals were the same as those obtained with the 25.4-cm. ones, so that the edge effect was negligible.

Measurement of Voltage. The voltage, E, applied to the test terminals, was obtained by reading the voltage on the low side of the testing transformer, and calculating E by the ratio of transformation. This ratio was 87:1, and was accurately determined. The voltage E', across the insulation can be calculated from the equation:

$$E' = \sqrt{E^2 + e_1^2 - 2\,E\,e_1 \sin\theta} \tag{17}$$

This equation can be derived from the geometry of Fig. 3. E, e_1, and θ are known as explained above, so that E' can be calculated.

Calculation of Losses. The watts lost in the two pieces of insulation under test are given by the equations:

$$W = E'\,I\cos\theta' \tag{18}$$

or

$$W = EI\cos\theta \tag{19}$$

Where the potential and current are in volts and amperes respectively. Equation (**18**) is the one that is always used, for it is desired to know both the voltage across the insulation and its power factor. This gives the total watts; watts per cu. cm. can be obtained by dividing the total watts by the actual volume of insulation under test.

One is likely to imagine that considerable time is required to secure data for one point, that is, data for calculating the power factor, the current, the voltage and the watts. As a matter of fact about 30 seconds are required to make the three exposures for each photograph, and about a minute more is required to obtain all the other necessary readings. We thus see that a considerable amount of data may be taken in a very short time. In about 10 minutes, we can secure data to give curves showing watts vs. voltage, current vs. voltage, and power factor vs. voltage.

An illustration of the cyclograph as it is set up in the small dark house, is shown in plate XLIX. Reference will be made to this in the section devoted to the development of the cyclograph, which will now be considered.

III. Development of the Cyclograph

A great deal has been written on the cathode ray tube but, regardless of the information given in the literature, it was found necessary to practically develop the tube from the beginning and to study carefully its characteristics. Little assistance has been derived from the literature because the object of this work was to develop tubes for commercial purposes. The tubes, therefore, must be reliable and constant in their operation over a period of several years. Tubes which will fulfill the requirements for this purpose must necessarily be superior to those required perhaps a few times a year. Tubes which are satisfactory to carry out investigations extending over a period of a few days or weeks, would not prove of value for investigations covering a period of several years. The desirability of having tubes ready for use at any time, just as a galvanometer is, has constantly been kept in mind. It is the writer's belief that this has now been accomplished, and tubes which have been used continually during the past two years indicate that reliable ones can be built without much difficulty.

Some of the important observations made in the development of the cyclograph and a comparison of the results obtained with those of other investigators will be given. A more detailed account of this is to be published elsewhere,[7] and it will not be necessary, therefore, to go into too much detail here. Reference should be made to the above mentioned article if one desires to go into this subject more fully than given below.

7. *General Electric Review*, July, 1915.

Vacuum Characteristics. Attention will first be given to the vacuum characteristics of cathode ray tubes. In the literature on this subject one will find that reference is made to trouble encountered with "hardening" and "softening" effects in these tubes. The "hardening" is an increase and "softening" a decrease of the vacua. These changes may occur either during operation or at other times. Several suggestions[8] have been made to counteract or eliminate these effects. There are four methods. The first, an auxiliary side tube made of platinum, or better still palladium, through which gas can enter the tube when the metal is heated for a few seconds at red heat. This method allows a reduction in vacuum but is useless for increasing it. The second, an auxiliary side tube containing acid sodium carbonate has been employed. This salt liberates a gas when a discharge of electricity takes place through it. Consequently, this auxiliary side tube possesses an electrode, and by passing a discharge between it and the anode the vacuum is reduced. This scheme, therefore, allows only a reduction in vacuum to be obtained. A third method is to have a side tube connected to the main tube through a stop cock. If the pressure becomes too small, a little gas is admitted from this side tube. Another side tube containing platinum-black, which readily absorbs large quantities of gases, is also connected to the cathode ray tube through a stop-cock. If the pressure becomes too great the platinum-black is allowed to remove a sufficient quantity of gas to give the desired vacuum. The fourth method is to have the cathode ray tube connected continually to an exhausting system. The vacuum can then be adjusted at any time to any desired degree.

Evidently, the first two methods of vacuum regulation are unsatisfactory for commercial work.

The third scheme is not suitable because slight changes in pressure affect the operation of the tubes greatly, and it is difficult to obtain fine regulation by operating stop-cocks. Such a scheme as this makes the construction of the tubes more complicated.

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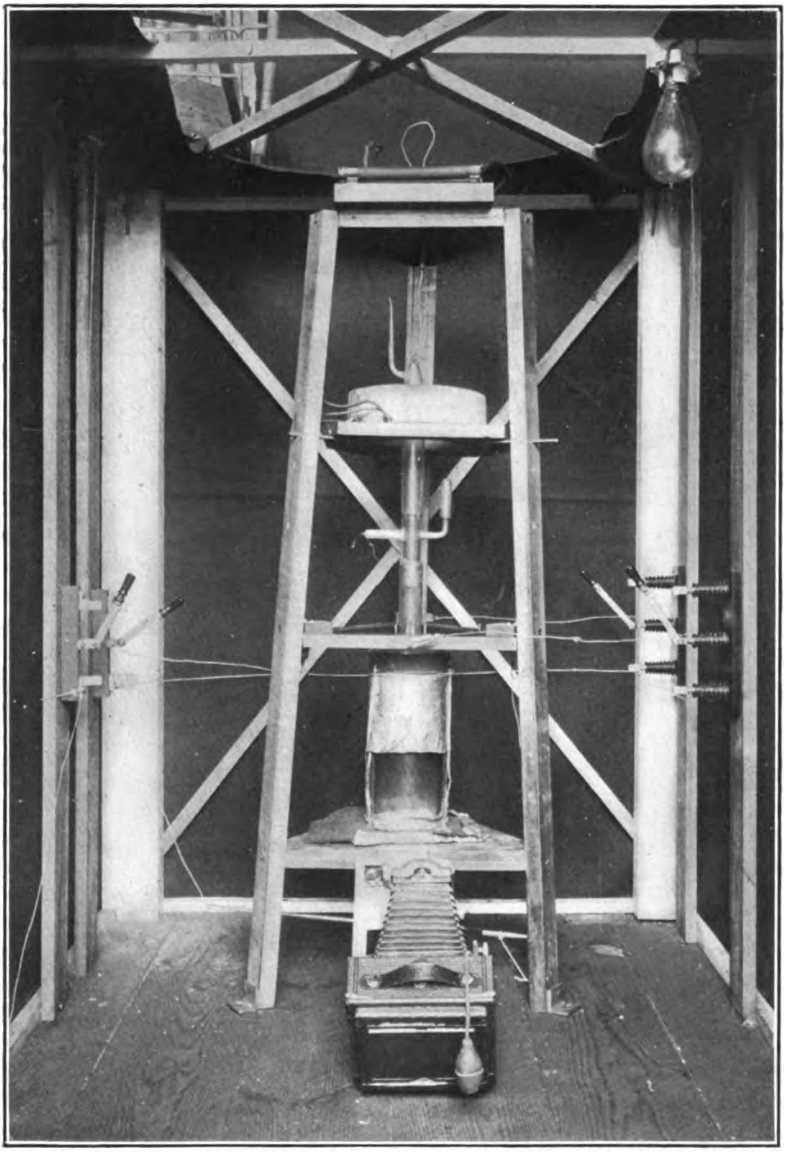
8. (*a*) *Loc. Cit.* (4), p. 530.

(*b*) "Apparate und Verfahren zur Aufnahme und Darstellung von Weckselstromkurven und elektrischen Schwingungen." H. Hausrath; Helios. Fach—*Zeitschift Fur Elektrotechnik*, Zeite 527, 1914.

(*c*) Siehe Z. B. Fortschnitte auf dem Gebiets der Röntgenstrahlen Bd 18, Heft 2, 1912, Heinz Bauer.



CYCLOGRAPH IN SMALL DARK ROOM [MINTON]

Likewise, the fourth method is unsatisfactory for one cannot afford to have suitable vacuum pumps installed where he desires to use the tubes.

These difficulties and objections lead to the belief that if satisfactory tubes were made it would be necessary to have them maintain constant vacua of the desired magnitudes under all ordinary conditions of operation. The development of such tubes was undertaken. It was finally shown that the vacuum "softened" because too much gas was adsorbed on the surface of the electrodes and glass walls. After the tubes had been operating for a few minutes, the vacua would rapdily decrease and would be entirely unsatisfactory for use. If too much adsorbed gas was liberated, then the tubes "hardened" because some of the gas was withdrawn from the interior of the tubes and adsorbed on the walls and electrodes. It was found, however, that if the tubes were exhausted three or four hours at perhaps 350 deg. cent. sufficient adsorbed gases were liberated from the glass walls and electrodes to maintain constant vacua over long periods of time. One tube has now maintained a constant vacuum for almost two years and there is no indication that it will not maintain this vacuum for a number of years, although it is used almost daily. Not one exception to this rule has been found. Some tubes have been operated about ten hours continuously with such strong rays that one could not touch the glass around the cathodes without receiving severe burns. Even in these most extreme cases, the vacua remained constant. It may be said, therefore, that when tubes are exhausted in this manner they will maintain constant vacua, thus requiring no vacuum regulators of any kind. This is not only a great improvement over tubes of other makes, but it insures reliable ones for experimental purposes.

It should be stated that one should be careful not to allow the pressure to increase to atmospheric value when once the tubes have been exhausted at a high temperature. If this should occur, it may be necessary to re-exhaust them at a high temperature in order to eliminate possible vacuum troubles. This has been found necessary several times.

Electrostatic Charges on Glass Surrounding Cathodes. Another difficulty was encountered in the development of cathode ray tubes. This difficulty was due to electrostatic charges which accumulated on the glass surrounding the aluminium cathodes. These charges were of a positive sign and, since the cathodes

where negative, it meant that discharges would occur between the cathodes and glass as soon as the potential differences reached a sufficient magnitude to cause the discharges. Such dicharges always caused the cathode ray streams to be unsteady, and frequently resulted in flash-overs within the tubes between the cathodes and anodes. The flash-overs were prevented by the use of high resistances (perhaps 100,000 ohms each), such as high resistance lightning arrester rods, in the cathode leads. These resistances should connect immediately to the cathode terminals as shown by *r* in Fig. 1. These resistances not only prevent flash-overs, but they also cause the tubes to operate much more steadily. They do not, however, prevent discharges from occurring between the cathodes and the glass surrounding them. A number of investigators have encountered this difficulty and have tried to eliminate it in various ways. To avoid this trouble Dr. Zenneck[9] surrounded the cathodes with glass formed into small cups as illustrated in Fig. 5A. Roschansky[10] for the same purpose, placed behind the cathodes metallic screens and filled the space between these and the glass with ruffled tinfoil leaves. This scheme is illustrated in Fig. 5B. where *S* is the metallic screen and *L* the ruffled tinfoil leaves. Grundelach, in his tube, made the cross section of the cathode almost large enough to fill the tube as illustrated in Fig. 5C.

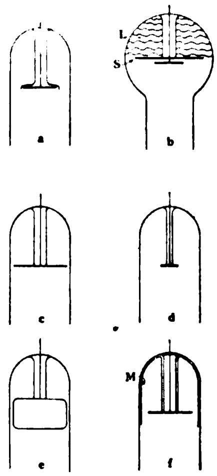


FIG. 5

A tube of Dr. Zenneck's design made in Germany was tried but the glass "Hinterkleidung" did not prevent static discharges between it and the cathode. It did, however, prevent them from occurring between the cathode and the glass wall of the tube. The discharges between the cathode and the glass "Hinterkleidung" caused unsteady cathode rays. The size, shape, and position of the cathodes and the kind of glass used have a great deal to do with the accumulation of these static charges and with the operation of the tubes. For example, cathodes of the shape shown in Fig. 5D give much trouble on account of the frequency of static discharges between them and the glass. Cathodes of the form shown in Fig. 5E are the most satisfactory; those il-

9. Zenneck—*Weid Ann* 69, p.842, 1899.
10. Roschansky-*Ann d. Phys.* 36, p. 281, 1911.

lustrated in Fig. 5c are quite satisfactory. It was found, however, that none of the schemes, with the exception of Roschansky's, which has not been tried, would prevent the trouble due to static discharges.

It was evident, therefore, that this trouble must be avoided by other means. It was noticed that tubes whose vacua "softened" during operation never gave any trouble due to these electrostatic charges. Tubes which had been exhausted several hours at a high temperature in order to eliminate vacuum changes are always unsatisfactory because of the difficulty with the charges. Since the adsorbed gases are liberated from the glass during exhaustion at about 350 deg. cent., it would seem that the reason the charges accumulate during operation of the tubes is on account of a film of gas on the glass being necessary for conducting away the charges. If a sufficient film is present on the glass, the charges are conducted to the cathodes and there neutralized, but if the film is removed, then the charges accumulate until they are neutralized by discharges between the cathodes and the glass. This phenomenon occurred with any form of cathode and with any kind of glass. It should not occur, say, in a tube whose cathode-end was constructed as shown in Fig. 5F where *M* is a metallic screen. This construction, however, was not necessary, for the following scheme of exhaustion was found to eliminate all trouble of this kind. The idea was to remove a sufficient amount of the film of gas by exhausting the tubes at a high temperature, in order to allow a constant vacuum to be maintained and still leave on enough of the film to conduct away the charges which collect on the glass surfaces. After some experimenting, it was found that if the tubes were exhausted at about 350 deg. cent. for perhaps a half hour, the vacua would remain constant during several hours of continuous heavy operation, and no trouble would be experienced on account of charges on the glass surrounding the cathodes. Exhaustion at a high temperature for this time was sufficient to avoid vacuum changes over long periods. This method of exhaustion has been tried on a number of experimental tubes and found to be satisfactory. One reason, therefore, why this trouble has been encountered so much is because the tubes have been exhausted for too long periods[11] at high temperature in order to avoid vacuum changes.

Regarding the kind of glass which will prove most satisfactory it may be said that soft sodium glass has given less trouble with

11. *Loc. Cit.* 8·(*b*) p. 527.

these static discharges than any other glass tried. This glass is also easy to work, and it is easier to adjust the time of exhausting at a high temperature to eliminate static charges and maintain a constant vacuum with this glass than with other kinds of glass tried.

Auxiliary Apparatus. Under auxiliary apparatus are classed the deflecting quadrants, means of exciting the cathode ray tube, the focusing coil, and the potential and current condensers. These will be briefly discussed in the order given.

(*a*) *The Deflecting Quadrants.* The method used to deflect the cathode rays is an electrostatic one, and for various reasons practically all investigators have the deflecting quadrants placed within the tubes instead of outside as shown in Fig. 1. If the deflections are proportional to the voltage impressed on the quadrants, then it is not at all necessary to place them within the tubes. These tubes have been in use during the past three years in the laboratory and it has never been found necessary to have the quadrants inside the tubes. With the single exception, described below, this law has always been obeyed. Since, therefore, these quadrants can be placed outside the tubes, it greatly simplifies their construction. It also permits easy adjustment of the magnitude of the deflections, a thing which is highly desirable in this work. The quadrants are made of pieces of brass about 0.5 in. by 1.0 in. and they must be supported by a material which has a very high insulation resistance and one which does not change due to surface leakage or otherwise. The reason for this is that the potential condenser is of small capacity and a small leakage current will cause the results to be considerably in error. It has been found that hard rubber serves this purpose nicely and accurate results can always be obtained with it. The hard rubber is never exposed to sunlight which causes its surface to deteriorate. The switches connecting the leads to the potential quadrants should have hard rubber bases with considerable leakage surface. Since the current condensers are so much larger than the potential one, it is not necessary to have such highly insulated switches. This does not mean however, that care should not be exercised with their construction.

One other important point in connection with the quadrants should be mentioned. During damp weather, moisture will deposit on the surface of glass. Formerly, this always happened with the cathode ray tubes, and sometimes it was im-

possible to even deflect the rays because the deposited moisture acted just like a metallic shield for the rays. In this condition reliable results could not be obtained, and, indeed, one was never certain of the results. It was necessary to make the tubes completely non-hydroscopic in the neighborhood of the quadrants in order to insure satisfactory results. Cellulose nitrate has been used for this purpose and it has been found quite satisfactory. This substance is made into a paste with ether and painted on the tubes with a brush over a distance of a few inches on either side of the quadrants. The paste soon dries leaving a layer of cellulose nitrate about 0.3 mm. thick over the surface of the glass. Since this procedure has been followed no inconsistencies of any kind have been observed, and this procedure is imperative for accurate results.

(*b*) *Excitation of the Tubes.* There are several methods which can be used for exciting the cathode ray tube. One method is the use of a high potential storage battery consisting of about 20,000 cells. The space occupied by this number of cells, each being about one inch by one inch by five inches in size, would be too large to make the use of the high potential storage battery of any commercial value. There are a number of other evident objections to the employment of the storage battery. The electrolytic rectifier was not satisfactory because it gave a fluctuating d.c. potential. The static machine has been used largely for operating the tubes especially in England and Germany. This machine, however, was not found to produce a sufficiently constant potential, especially during damp weather, to maintain steady cathode rays as required for the cyclograph. The kenotron,[12] which has been developed by the Research Laboratory at Schenectady, has been tried as a means of exciting the tubes. This apparatus has not been used extensively, but it produces a steady cathode ray stream, and there is no apparent reason why it could not be used to good advantage in this work. It is quite simple in its construction and operation.

The mechanical rectifier has been largely used in connection with the cyclograph for producing the cathode rays. The form of commutator used and the diagram of connections are illustrated in Fig. 6. The commutator, *R*, is connected to the

12. "A New Device for Rectifying High Tension Alternating Currents—The Kenotron." Saul Dushman, *General Electric Review*, Vol. 18, pp. 156-167, March, 1915.

shaft of a small four-pole, motor generator set which supplies the low tension of the 60 cycle transformer, *T*. The commutator can be adjusted so that it will rectify the peaks of the a-c. wave. The rectified direct potential charges the condenser, *C*, to a voltage corresponding to the adjustment of the commutator. The condenser, *C*, supplies the direct potential to operate the tubes. The energy consumed by the tubes is so small that they operate quite steadily, thus showing that the potential of the condenser remains practically constant. This condenser consists of four ordinary Leyden jars connected in parallel. The present commutator will operate up to about 30,000 volts which is all that is required for the tubes. Care must be taken to have good contacts between the brushes and the segments, because poor contacts in the system supplying the direct potential for the tubes cause unsteady cathode rays. One essential for good contacts is to adjust the brushes so that they are almost tangent to the commutator. Fibre gives sufficient strength and insulation for the commutator. The only metal parts are the segments, brushes, and connecting strips, *a* and *b*.

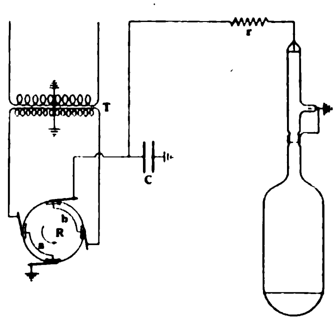


Fig. 6

(*c*) *Focusing Coil.* Prof Ryan[13] and Mr. Rankin[14] have said much concerning the focusing coil, *F* (Fig. 1), and its use in concentrating and increasing the brightness of the fluorescent lines on the screen. It will not be necessary, therefore, to discuss this apparatus and its action for it would simply be repeating what they have already said. It will be well to emphasize, however, that it is necessary for the axis of the focusing coil and tube to exactly coincide. If this condition is not fulfilled, then the figures on the screen will not be symmetrically located with respect to the center. Neither the area of an ellipse nor the magnitude of the deflections is changed by moving them over the screen with the focusing coil, so that no error is introduced into the results by not having the above conditions carried out, but one who is not familiar with the character-

13. *Loc. Cit.* (4) p. 527-528.

14. Rankin "Use of a Magnetic Field with the Ryan Cathode Ray Oscillograph" *Phys. Review*, Vol. 21, pp. 399-406, 1905.

istics of the tubes might be inclined to look with skepticism upon the results.

It has been stated that only the brightness of the fluorescent spot on the screen and not its size is affected by the use of the focusing coil. The observations, which have been made in connection with the development of the cyclograph, do not bear out this statement. When the coil is placed just above the plane of the quadrants, the spot and the lines are not only magnified in brightness for the same applied potential, but they are also finer and much more sharply defined. This would be the proper place for the focusing coil if it were not for the effect of the magnetic field superimposed on the electrostatic field. The focusing coil is always placed so that its plane coincides with that of the cathode.

(*d*) *Potential and Current Condensers.* The potential condenser consists of hollow metallic tubes with their ends closed by semi-spherical caps. About six of these are joined together with metallic rods and supported from the ceiling with insulators. Two such plates constitute the outer plates of the potential condenser, C_3, shown in Fig. 1. The inner plates are about 2½ ft. by 2 ft. by ⅛ in. The middle one is grounded and supported firmly, while the two adjacent ones on either side are supported from the ceiling with hard rubber. These hard rubber supports are necessary for the reason stated in the section on "Deflecting Quadrants." It is essential to have air as the dielectric for the potential condenser because an error would be introduced into the results if the phase angle of it were not 90 degrees. In the theoretical discussion of the cyclograph, it was assumed that the phase angle was 90 degrees.

The current condensers should have air for the dielectric for, at least, four reasons. First, if these condensers are broken down as they are when the test pieces are broken down then those with air dielectrics are self-restoring. Those with other dielectrics might be broken down and cause one considerable trouble in repairing them. Second, it is necessary to have current condensers which never change in capacity. The air condensers used have not changed more than one per cent in capacity during the past two and a half years. Condensers with other dielectrics would likely cause errors in the results due to capacity changes. Third, if condensers with dielectrics other than air are used, then it is necessary to correct the results for the losses in them. It is better to eliminate these

losses rather than correct for them. Fourth, in the formulas used for calculating the current and power factor of the insulation, a perfect condenser was assumed. These current condensers are constructed so as to have the minimum current possible pass through the supporting frames.

Peculiarities of the Tubes. At this stage it will be well to refer to several points to which attention should be given in order to insure steady operation of the tubes. The first is that care must be taken to eliminate the disturbing effects due to stray magnetic and electric fields. The cathode ray stream should be actuated only by the field applied to the quadrants. Now, the tubes are operated at about 15,000 to 25,000 volts so that a very strong field exists around the cathode lead. This field has caused much unsteadiness in the cathode rays and has given much trouble in taking current readings with the "static voltmeter and condenser shunt method." For this reason the cathode leads should be small, well insulated, lead covered cables, the sheath being grounded. These cables act as part of the condensers used to supply direct potential for the tubes. So that the resistance, *r*, must be placed as shown in Fig. 6. If it were placed between the condenser and the lead rather than between the lead and cathode, then the tube would be unsteady. In order to completely shield the rays and the leads connected to the quadrants from this field, it is necessary to have a thin metallic hood of some sort extending down almost to the quadrants and up to the cathode lead. The resistance, *r*, is then placed within this hood. This precaution prevents the "jumping" of the figures on the screen due to the field around the cathode lead. It is well to have metallic cylinders over the large part of the tubes as shown in plate XLIX. The hole which is seen in the cylinder is for the purpose of allowing photographs to be taken. Such a procedure as this will eliminate much unsteadiness of the rays and prevent the figures on the screen from "jumping." This sort of trouble appears to have been encountered before[15] but apparently it was not eliminated.

Prof. Ryan found it necessary[16] to cover the surface of the tubes from the anodes extending past the cathodes with a thick paraffine jacket to avoid irregularity in the cathode ray streams due to corona forming on the cathode leads where

15. *Loc. Cit.* 8 (*b*) p. 528.
16. *Loc. Cit.* (4) p. 529-530.

they enter the glass. This corona formation has been observed frequently but, after the cause of unsteadiness mentioned above was eliminated, no irregularity of the cathode ray streams was observed due to this corona formation. It is not necessary, therefore, to provide the tubes with insulating jackets around the cathodes.

Another peculiarity noticed was that when high voltages (3000 or 4000) were applied to the quadrants (due to large losses in the insulation) small areas were obtained when the separate deflections (*a* and *b*) were being photographed. These could not be due to a potential applied to the opposite set of quadrants because they were grounded while the photographs of the other deflections were being taken. These areas were due to fields set up between the leads connected to the upper portions of the switches (See Fig. 1). Leads connected to each pair of quadrants came down on opposite sides of the tube and about 12 in. apart. After the wires of each pair of leads were brought down together and connected to the quadrants no further trouble was experienced from this source. These areas were quite noticeable because the potential and current were almost in phase with each other; this condition may be obtained in insulation, as we shall soon see.

In regard to the salt used for the fluorescent screen, it may be said that calcium tungstate ($CaWO_4$) and a zinc sulphide (ZnS) are the most strongly fluorescent salts when acted upon by cathode rays. The former salt is more strongly fluorescent for the weaker rays while for very strong rays the latter salt is the more strongly fluorescent. Both of these substances however, will be found useful in making the screens.

Considerable space has now been devoted to the theory of the cyclograph and its development. The remaining portion of the paper will be devoted to a study of dielectric losses and other electrical properties of insulation, such a study being made possible by the development of the cyclograph for this work. The results of some of the tests will first be given and a discussion of them will follow.

IV. Experimental Results

In section II. it has been shown how the dielectric loss, power factor, and current for a piece of insulation are determined. (See equations **18**, **16**, and **15**). These quantities have been determined for a number of different insulating materials

and have been plotted against the applied voltage, the temperature, and per cent absorbed moisture in the case of paper. Since a very large amount of data on insulation has been taken with the cyclograph during the past three years, it will be possible to incorporate only a small portion of it, in this paper. A sufficient amount of it, however, will be given in the form of curves to enable one to obtain a general idea of what is taking place within a piece of insulation when it is subjected to a high voltage stress under various conditions. These curves will also give one a knowledge of the magnitude of the quantities involved. Section V. contains a closer study of these experimental results and empirical equations are given to represent the results mathematically.

All the tests embodied in this paper have been made at 60 cycles with a generator which produces a very nearly a sine wave. The tests were made in good transformer oil to avoid corona and the brass test terminals were either 20 cm. or 25.4 cm. in diameter and 0.5 cm. thick. They were square-edged and arranged so that they could be clamped into position after good contact was obtained.

The original data from which the results were calculated need not be given here. The calculated data, however, are given in the form of curves. The tables from which the curves were plotted are omitted for the sake of brevity. For the purpose of illustrating how the original data are taken and the results calculated, there are given below two tables on oil-treated pressboard, sample No. 2, the results on which are given in a later section and shown graphically in Figs. 19, 20 and 21. It should be stated that the results given in this paper were obtained from data taken for other purposes. For this reason it was necessary, in the case of varnished cloths and in the case of the effect of moisture in pressboard, to take the plotted points off of other curves. In the case of all the other results incorporated in this paper the points represent actual data taken. It should also be stated that some of the units used were English while the others were metric. It is customary in this country to express voltages in volts per mil and thickness in inches. If the metric units had been used it would have been necessary to change them in the English units for comparative purposes. In order to avoid this the English units were used in these cases. In all other cases the metric units were used because it is much better to start think-

ing in metric rather in English units when there is no standard already established.

ORIGINAL DATA.

Date: 12-14-14.
Generator: sine wave, No. 1080.
Test terminals: 20 cm. square edged.
Frequency: 60.5 cycles.
Temperature: 60.0 deg. cent.
Volts on tube: 21,500.
Focusing coil: 1.5 amps.
Exposure: Ellipses, each 10 sec.
Cross lines, each 5 sec.
Material: 3/32-in. oil-treated pressboard.
Sample: Two sheets, A. and B (see Fig. 1).
Average thickness of sample: (0.470 cm.) 0.185 in.
Total volume under test: 147.7 cu. cm.

Photo No.	Gen. Volts	Volts on Paraffine Condenser (Fig. 4 B) A	B	Section	Combination of Air condensers
1	141.	49.3	54.2	2	1, 2, 3, 4 series
2	234.	78.5	87.5	2	" "
3	361.	52.0	53.5	3	" "
4	460.	69.5	72.0	3	1, 2 "
5	552.	82.5	86.3	3	" "
6	458.	69.0	71.8	3	" "

In the table below one will find the calculated results of the above table. The following explanatory remarks apply to this table: a and b are the horizontal and vertical semi-axes, respectively, of the photographs; a' and b' are the major and minor semi-axes of the ellipses respectively. Cos θ is the power factor of the circuit, while cos θ' is that of the insulation. The former is equal to $\frac{a'\,b'}{a\,b}$, while the latter is given by equation (**15**). By means of calibration curves the readings in columns A and B of the above table give the voltage e_1, see Fig. 4B. The averages of A and B which are always nearly equal, are given in the table below. These average values are used to determine, I, also given in the following table. I is calculated by means of equation (**16**), This equation yields the following equations for the various combinations of condensers used: $I_1 = 0.0000186\, fe_1$, milliamperes, for first combination in the above table; $I_2 = 0.0000197\, fe_1$, milliamperes, for the second combinations; $I_3 = 0.0000439\, fe_1$, milliamperes, for the third combination; f is the frequency. The

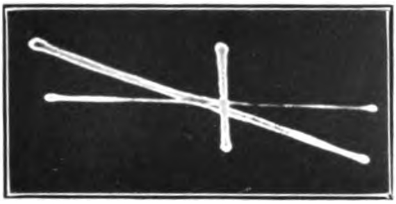
equations give the total current passing through the insulation; the current per sq. cm. is obtained by dividing by 314 sq. cm., the area of test terminals. The current values are given in milliamperes per sq. cm. E, in kv., is obtained from the generator volts by multiplying by 87.0 ± 1 per cent, the ratio of transformation of the testing transformer. E', in kv., is calculated by means of equation (**17**). The volts per mil (V.P. M.) are obtained by dividing E' by the total thickness. The total watts are calculated by means of equation (**18**); dividing by the volume of the insulation, one obtains the watts per cu. cm. In this way the following results were calculated from the above table:

RESULTS CALCULATED.

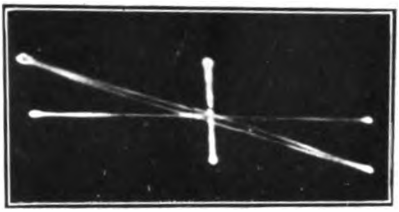
Photo No.	a cm.	b cm.	a' cm.	b' cm.	Cos θ per cent	Cos θ' per cent	Ave. cond. volts	I ($m.a.$) sq. cm.	E kv.	E' kv.	W C. C.	V.P.M
1	1.13	0.55	1.28	0.050	10.3	11.3	1055	0.00379	12.3	11.2	0.0101	60.
2	1.77	0.85	2.00	0.058	7.7	8.4	1685	0.00605	20.3	18.5	0.0199	100.
3	2.49	1.28	2.85	0.065	5.8	6.3	2440	0.00930	31.4	28.9	0.0359	156.
4	1.55	1.60	2.13	0.060	5.1	5.3	1465	0.0124	40.0	38.5	0.0537	208.
5	1.83	1.52	2.43	0.050	4.4	4.6	1745	0.0148	48.0	46.2	0.0667	249.
6	1.54	1.30	2.05	0.047	4.8	5.0	1455	0.0123	39.8	38.3	0.0502	207.

As a further means of illustrating how the results are obtained there are given in plate L reproductions of a series of six photographs taken on a sample of varnished cloth at 200 volts per mil. and at various temperatures. These illustrations show that the figures on the flourescent screen are very steady and well defined. From these illustrations the power factors (cos θ) are determined. The following table gives the measurements made on the negatives. The plates used were the American lumiere sigma.

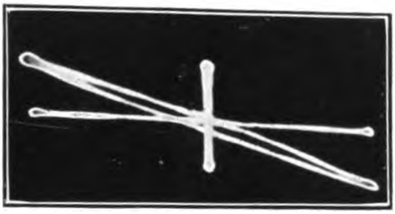
Photo No.	a cm.	b cm.	a' cm.	b' cm.	Cos θ per cent	Cos θ' per cent	Temp. deg. cent.
1	2.70	0.85	2.91	0.045	5.7	6.3	30.0
2	2.79	0.85	3.05	0.055	7.1	7.9	71.0
3	2.83	0.87	3.12	0.102	12.9	14.4	99.5
4	2.90	0.87	3.17	0.187	23.5	26.2	115.0
5	1.55	0.85	1.83	0.290	40.3	42.2	130.0
6	1.93	0.88	2.15	0.515	65.2	68.6	145.0



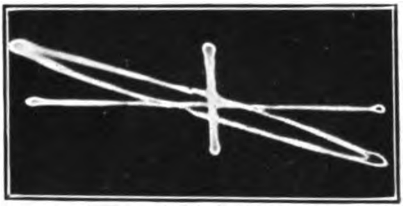
No. 1 [MINTON]



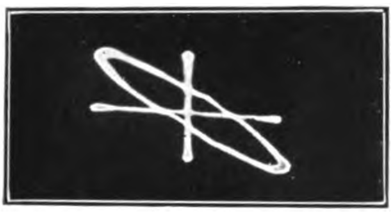
No. 2 [MINTON]



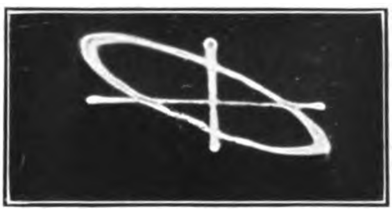
No. 3 [MINTON]



No. 4 [MINTON]



No. 5 [MINTON]



No. 6 [MINTON]

A. Varnished Cloths. A large number of tests have been made on various kinds of varnished cloths. The different test samples were about 30 cm. square, and were built up of separate sheets of the same size to the required thickness. Ordinarily, each of the test pieces, *A* and *B*, (see Fig. 1) consisted of four or five sheets of varnished cloth assembled under oil, or bound together by thin oil-films, and placed between the test terminals in the oil box. Either method of assembly will yield the same results, as long as good contact is maintained between

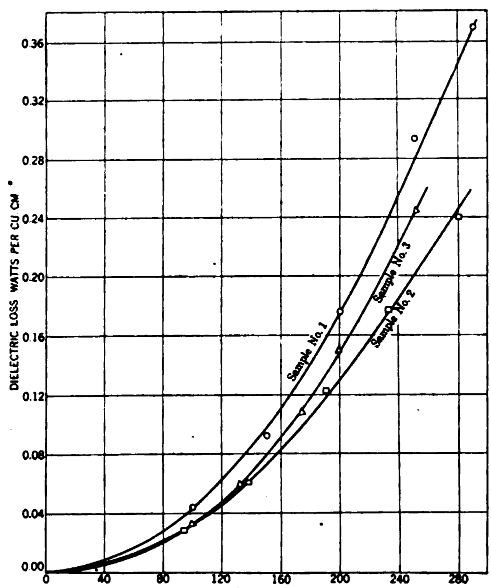


FIG. 7—TWELVE-MIL BLACK VARNISHED CLOTHS

Comparative curves showing dielectric loss vs. volts per mil for three different kinds at 100 deg. cent. 60 cycles—sine wave—total thickness: 1—0.1214 in; 2—0.1245 in; 3—0.1093 in.

the terminals and test pieces. Tests made on samples ranging from four to twelve sheets also yield the same results.

In Figs. 7 to 12, inclusive, are illustrated some of the results taken on various kinds of varnished cloths. It is seen that the current values in Fig. 9 fall nicely on the lines, but in Fig. 10 quite the contrary conditions is noticed. No doubt a large part of this inconsistency is due to the initial condition of the material and to the effect of temperature in producing definite changes in it. Changes of this nature have been noted by

other observers.[17] For sample No. 1, it is seen that the losses at 138 deg. cent. are forty five times as great as they are at 25 deg. cent. and for sample No. 2, the ratio is twenty five to one. All the curves shown in Figs. 7 to 12, inclusive, are consistent in showing that No. 1, No. 3 and No. 2 represent the order in which the samples should be placed, as far as representing their insulating value is concerned.

It will be interesting to compare these results on varnished cloths with those on some others. In one instance, with

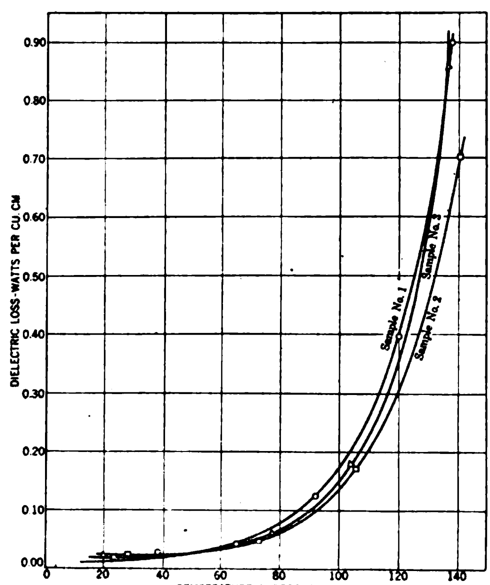


FIG. 8—TWELVE-MIL BLACK VARNISHED CLOTHS

Comparative curves showing dielectric loss vs. temperature for three different kinds at 200 volts per mil—60 cycles—sine wave—total thickness: 1—0.1214 in; 2—0.1245 in; 3—0.1093 in.

another varnished cloth at about 200 volts per mil. and 100 deg. cent. the watts per cu. cm. were about 4.0, the per cent power factor 98, and the milliamperes per sq. cm. about 0.050. Comparing these values with those given in Figs. 7 to 12, inclusive, one will note the following points; watts per cu. cm. at 200 volts per mil. and 100 deg. cent. are about twenty three times as great for the above cloth as they are for sample No. 1; the current value is about five times as great and the power factor

17. *Loc. Cit.* (3) p. 365.

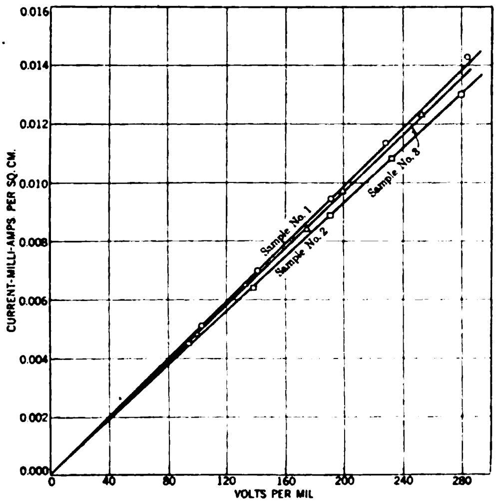


FIG. 9—TWELVE-MIL BLACK VARNISHED CLOTHS

Comparative curves showing current vs. volts per mil—for three different kinds at 100 deg. cent.—60 cycles—sine wave—total thickness: 1—0.1214 in; 2—0.1245 in; 3—0.1093 in.

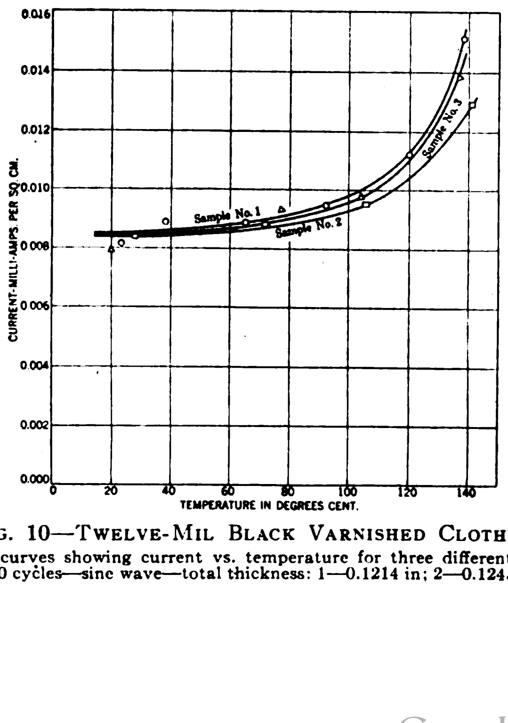


FIG. 10—TWELVE-MIL BLACK VARNISHED CLOTHS

Comparative curves showing current vs. temperature for three different kinds at, 200 volts per mil—60 cycles—sine wave—total thickness: 1—0.1214 in; 2—0.1245 in; 3—0.1093 n.

about four and a half times as great for the former cloth as for the latter. On the other hand, another sample of varnished cloth has yielded a power factor at 100 deg. cent. of about 13.5 per cent compared with about 20 per cent as shown in Fig. 11. These numbers show in a striking manner the difference likely to be

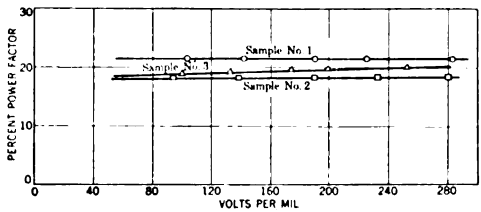


FIG. 11—TWELVE-MIL BLACK VARNISHED CLOTHS

Comparative curves showing per cent power factor vs. volts per mil for three different kinds at 100 deg. cent.—60 cycles—sine wave—total thickness; 1—0.1214 in; 2—0.1245 in; 3—0.1093 in.

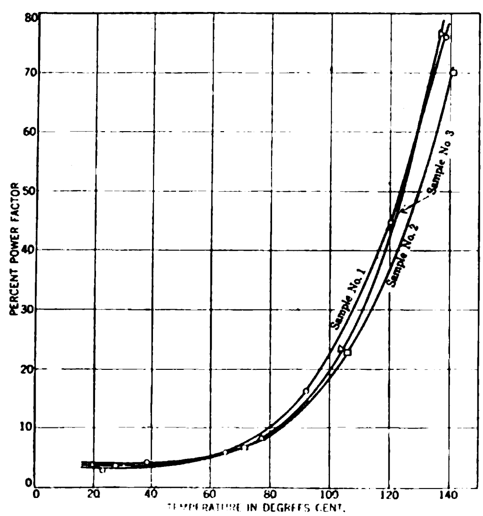


FIG. 12—TWELVE-MIL BLACK VARNISHED CLOTHS

Comparative curves showing per cent. power factor vs. temperature for three different kinds at 200 volts per mil—60 cycles— sine wave—total thickness: 1—0.1214 in; 2—. 0.1245 in; 3—0.1093 in.

found in various kinds of varnished cloths, and they also show that tests of dielectric losses yield most valuable results. When a loss of 4.0 watts per cu. cm. is observed in a piece of insulation whose volume is about 250 cu. cm., it means that about a kilowatt is producing heat in it. Under such severe conditions a piece of insulation will always be punctured within a few minutes.

B. Oil-Treated Pressboard. The samples of pressboard used were about 30 cm. square and were cut from regular 3/32-in. stock. After receiving a certain amount of drying, the samples were impregnated with good transformer oil for several hours. The results on the samples of pressboard, selected for this paper, were chosen so as to be able to show the characteristic curves and to compare the results for similar insulation under different conditions. Each of the test pieces, *A* and *B*, (see Fig. 1)

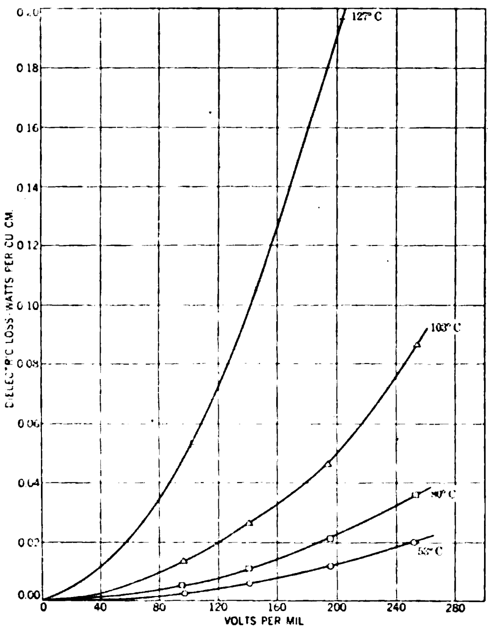


FIG. 13—SAMPLE NO. 1—3/32-IN. OIL-TREATED PRESSBOARD

Comparative curves showing dielectric loss vs. volts per mil at four different temperatures 60 cycles—sine wave— total thickness 0.193 in.

consisted of one sheet of oil-treated pressboard of the dimensions given above.

Figs. 13 to 18, inclusive, show a set of curves taken on pressboard sample No. 1. The figures which have temperature as the abscissas were obtained from those having volts per mil as their abscissas. Attention should be called to the fact that the power factor was observed not to change with voltage for this sample at 53 deg. cent. and 80 deg. cent. For this reason one photograph only was taken at each of these two temperatures. These two power factors were used in making calcula-

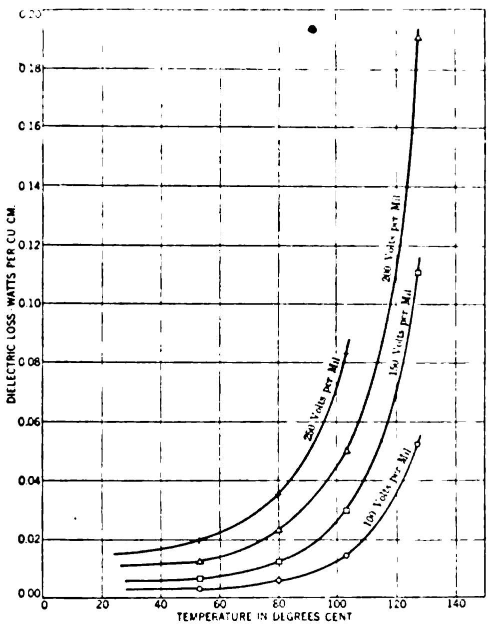


Fig. 14—Sample No. 1—3/32-in. Oil-Treated Pressboard

Comparative curves showing dielectric loss vs. temperature at four different voltages—60 cycles—sine wave—total thickness 0.193 in.

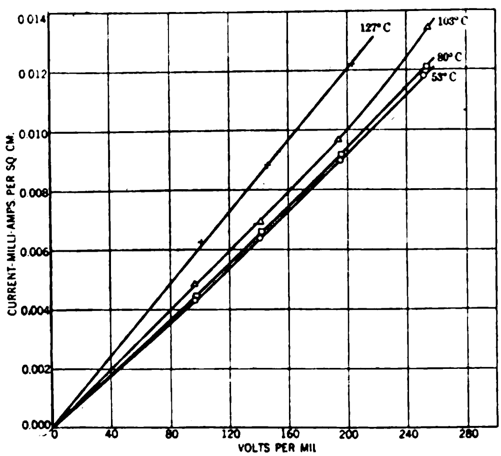


Fig. 15—Sample No. 1—3/32-in. Oil-Treated Pressboard

Comparative curves showing current vs. volts per mil at four different temperatures—60 cycles—sine wave—total thickness 0.193 in.

tion of watts at the different voltages for these two temperatures. Such a procedure as this would not be justified if the power factor changed with the applied voltage.

All the current curves shown in Fig. 15, with the exception

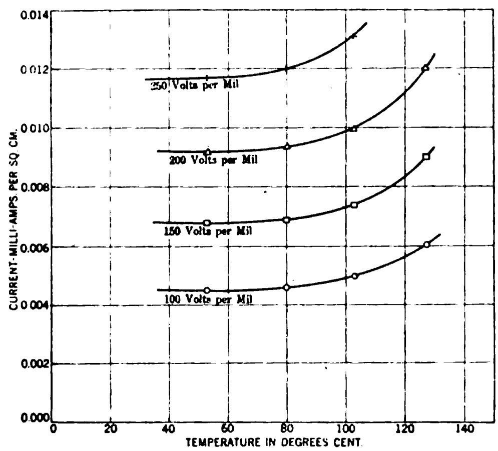


FIG. 16—SAMPLE NO. 1—3/32-IN. OIL-TREATED PRESSBOARD
Comparative curves showing current vs. temperature at four different voltages—60 cycles—sine wave— total thickness 0.193 in.

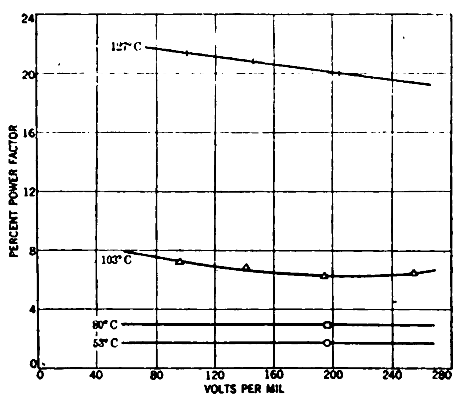


FIG. 17—SAMPLE NO. 1—3/32-IN. OIL-TREATED PRESSBOARD
Comparative curves showing per cent power factor vs. volts per mil at four different temperatures—60 cycles—sine wave—total thickness 0.193 in.

of the one at 127 deg. cent., curve upward near the upper ends, thus showing that the insulation was weakening. After taking the reading at 204 volts per mil. and 127 deg. cent, the voltage was increased to secure a reading at 250 volts per mil., but before it could be taken the pressboard broke down.

Results on two other samples (No. 2 and No. 3) of oil-treated pressboard, of the same kind as sample No. 1, are shown in Figs. 19 to 24 inclusive. These are for comparison with sample No. 1. Curves are not given for samples No. 2 and No. 3 showing dielectric loss, current, and power factor plotted against temperature. These three quantities, however, are plotted against voltage at 28 deg. cent., 60 deg. cent. and 85 deg. cent. The effect of temperature, therefore, up to 85 deg. cent. can be noticed and a comparison made with sample No. 1.

It is worth while to compare the losses of samples No. 2 and No. 3 here. Considering the curves in Figs. 19 and 22, it it seen that at 27 deg. cent. and 28 deg. cent. the losses for sample No. 2 are about half of those for sample No. 3 at the higher

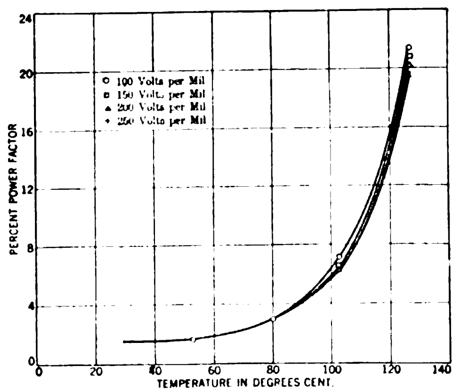


FIG. 18—SAMPLE NO. 1—3/32-IN. OIL-TREATED PRESSBOARD

Comparative curves showing per cent power factor vs. temperature at four different voltages—60 cycles—sine wave—total thickness 0.193 in.

voltages, while at the lower voltages the reverse is true. At 60 deg. cent. the losses in the former sample are about one-tenth of those for the latter sample at the higher voltages, but at the lower voltages they are about one-third as large. For the higher voltages the losses in sample No. 2 at 85 deg. cent. are about one-thirtieth of those in sample No. 3 at the same temperature, but they are about one-eighth as much at the lower voltages for the same temperature. These numbers show that temperature has an enormous effect on sample No. 3 compared with sample No. 2. They also show that a peculiar phenomenon of some nature occurs as the applied voltage is increased, otherwise the above peculiarities would not occur. This same effect is present at the higher temperatures because

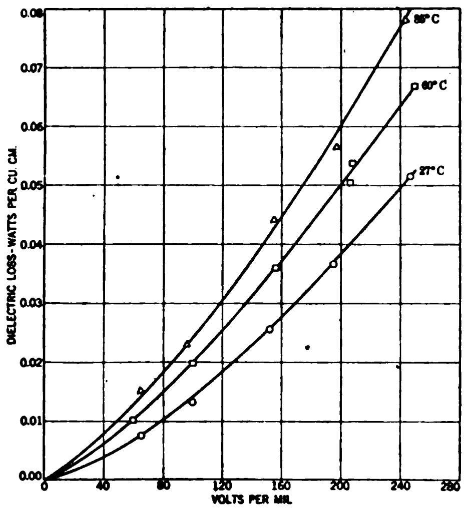


FIG. 19—SAMPLE NO. 2—3/32-IN. OIL-TREATED PRESSBOARD

Comparative curves showing dielectric loss vs. volts per mil at three different temperatures 60 cycles—sine wave—total thickness 0.1855 in.

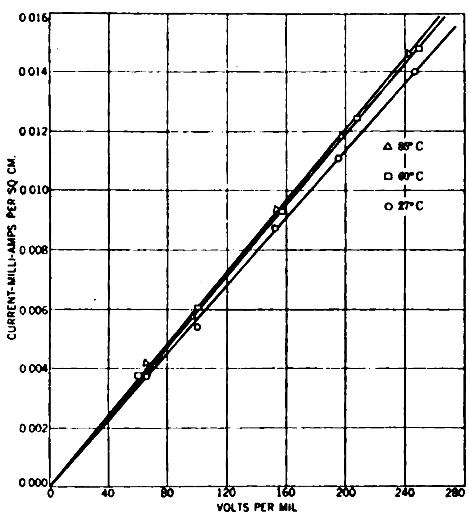


FIG. 20—SAMPLE NO. 2—3/32-IN. OIL-TREATED PRESSBOARD

Comparative curves showing current vs. volts per mil at three different temperatures—60 cycles—sine wave—total thickness 0.1888 in.

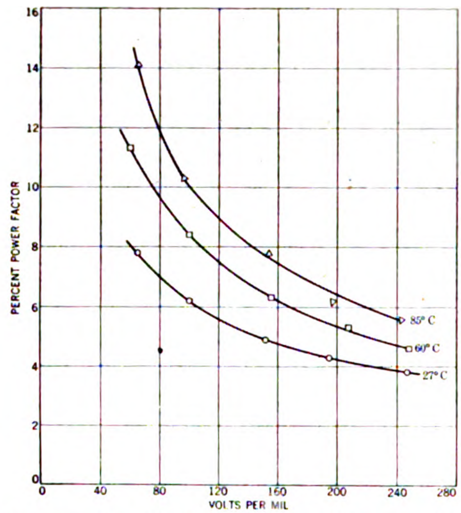


Fig. 21—Sample No. 2—3/32-in. Oil-Treated Pressboard

Comparative curves showing per cent power factor vs. volts per mil at three different temperatures—60 cycles—sine wave—total thickness 0.1855 in.

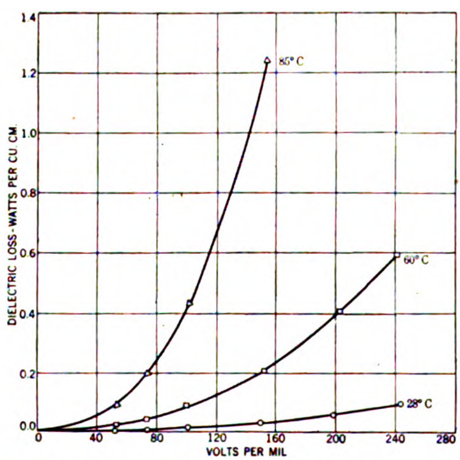


Fig. 22—Sample No. 3—3/32-in. Oil-Treated Pressboard

Comparative curves showing dielectric loss vs. volts per mil at three different temperatures—60 cycles—sine wave—total thickness 0.199 in.

the ratio of the losses in the two samples is much less at the lower voltages than at the higher ones. These peculiarities observed for the losses are due to the decrease in power factor with increasing voltage for sample No. 2 as shown in Fig. 21. The set of curves for sample No. 2 shows that the pressboard was not weakening rapidly as the temperature was increased, but those for sample No. 2 show very large weakening effects due to increase of temperature.

One is surprised to observe such large variations in the losses, power factors, and current values for the same insulations

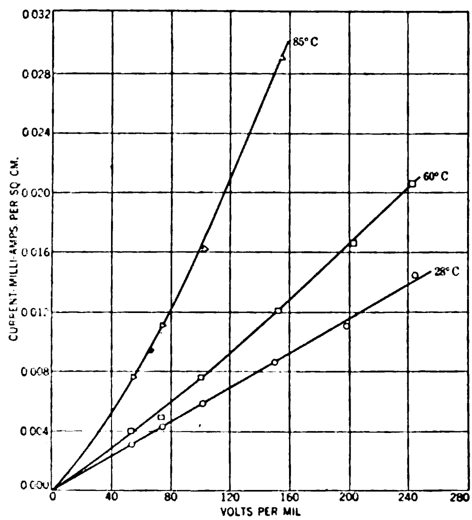


FIG. 23—SAMPLE NO. 3—3/32-IN. OIL-TREATED PRESSBOARD
Comparative curves showing current vs. volts per mil at three different temperatures—60 cycles—sine wave—total thickness 0.199 in.

under the same voltage and temperature conditions. The explanation of these variations is found in the quantity of absorbed moisture the samples contained. These three samples of oil-treated pressboard contained different amounts of absorbed moisture and for this reason their electrical properties were quite different. Samples No. 1, No. 2, and No. 3, contained about 0.5, 1.0 to 1.5, and about 5.4, per cent free moisture respectively. Since sample No. 2 had considerable drying it may be that certain effects were produced, due to this, that caused the power factors to behave as shown in Fig. 21. This will be referred to in the next section dealing with a study of the

experimental results. It may be asked then how much of the losses, power factors, and current, is due to moisture and how much is due to the material itself? The answer to this question has been determined as shown in the next section.

C. Effect of Moisture in Oil-Treated Pressboard. In order to determine how the losses, power factors, and current for oil-treated pressboard are affected by the quantity of absorbed moisture, a number of samples of the same kind of pressboard as tested above was taken. These samples were about 30 cm. by 35 cm. cut from the regular 3/32-in. stock. They were placed in a closed can for about two weeks just prior to begin-

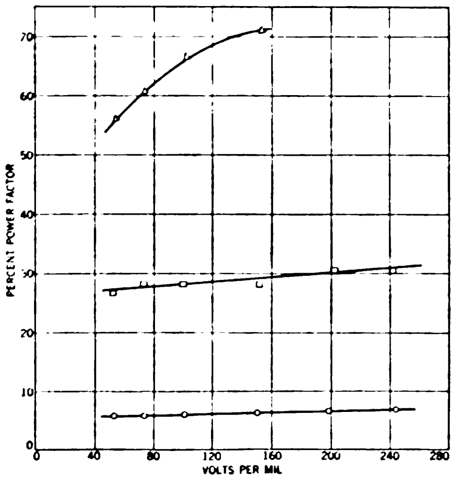


FIG. 24—SAMPLE NO. 3—3/32-IN. OIL-TREATED PRESSBOARD

Comparative curves showing per cent power factor vs. volts per mil at three different temperatures -60 cycles—sine wave—total thickness 0.199 in.

ning the tests. During this period the samples had sufficient time to liberate or absorb moisture until all of them contained equal percentages.

When a test was ready to be made, two sheets were taken out of the can. Two strips, about 2.5 cm. by 30 cm. were cut from each sheet, and from the four strips thus obtained, eight samples, 2 cm. by 5 cm. were cut from various places. These small samples were placed, at once, in an air-tight weighing bottle. The test samples, 30 cm. square, were weighed at the same time the moisture samples were put in the air-tight weighing bottle. The square samples were then dried in air at 100 deg. cent. until they had lost the desired amount of mois-

ture. They were then weighed in an air-tight receptacle, and their weight determined before any moisture could be absorbed. After weighing, the samples were placed at once in good transformer oil at about 65 deg. cent. in order to be sure that no moisture was absorbed by exposure to the air and to avoid the possibility of liberating appreciable quantities of water during impregnation at 65 deg. cent. From these data, the percentage loss of weight due to vaporizing moisture was determined. By securing the weights of these small moisture samples before and after drying them at about 90 deg. cent. in vacuo, it was possible to calculate the total free moisture they contained. Phosphorous pentroxide tubes were used to absorb the water liberated during the drying. This percentage of free moisture in the small samples was taken to represent the percentage absorbed moisture in the test pieces. Subtracting from this value the value obtained above for the loss of weight due to drying in air at 100 deg. cent., one obtained the percentage absorbed moisture still remaining in the test pieces during the tests. Absolutely correct results cannot be obtained by this method, but approximately correct percentages can be secured.

In Figs. 25, 26 and 27 will be found results taken at 200 volts per mil and at three different temperatures on several sheets of pressboard containing different percentages of moisture. It is to be regretted that more points are not available through which the curves may be drawn. Sufficient points, however, were taken to give the general shape of the curves and to show the enormous influence absorbed moisture has on the losses, power factors, and current values for porous insulation capable of absorbing moisture. The value 0.5 per cent moisture was estimated from previous experience. Attention should be called to the point at 99 per cent power factor given in Fig. 27. At 150 volts per mil the recorded power factor was 99 per cent, but while attempting to take the reading at 200 volts per mil the test pieces broke down. From previous experience, therefore, it was known that the power factor at 200 volts per mil and 85 deg. cent. could not have been less than 99 per cent. For this reason this point was used to give the direction of the curve near 100 per cent power factor.

At lower voltages (50 to 100 volts per mil) there is a decided "dip" in the curves similar to those shown in Fig. 27 at about 2.0 per cent moisture. At the higher voltages (250 volts per

mil) and temperatures this "dip" is not present. Too much space would be required to show all of these effects by means of curves, and for this reason they are omitted. It is questionable, therefore, whether all the moisture should be removed or not. Other interesting points will be brought out in the study of the experimental results given next.

V. Study of Experimental Results

Empirical Equations. In order to study the subject more carefully, it will be advantageous to express the results in the

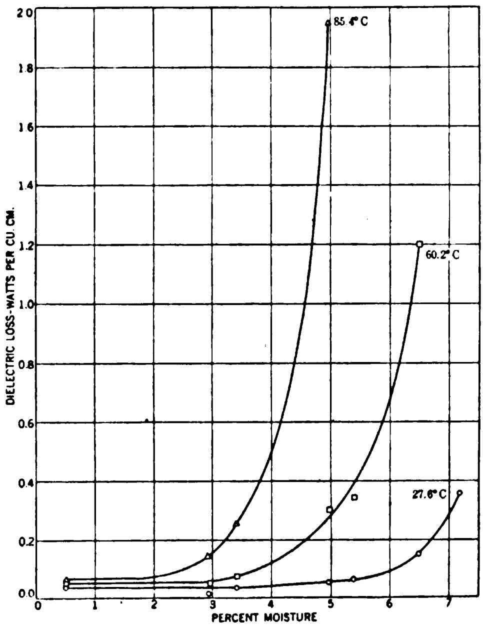


Fig. 25—Oil-Treated 3/32-in. Pressboard

Comparative curves showing dielectric loss vs. per cent moisture at three different temperatures and at 200 volts per mil—60 cycles—sine wave—average thickness of the seven samples used was 0.196 in.

form of empirical equations. By this means, a comparison of the results lead to a better understanding of them and will show clearly the fundamental nature of all of the results given in this paper. In experimental results, the order in which the figures were given was dielectric loss, current, and power factor. This order will now be reversed, and equations for current and power factors followed by those for dielectric losses will be given as a function of the voltage, temperature, and per cent moisture.

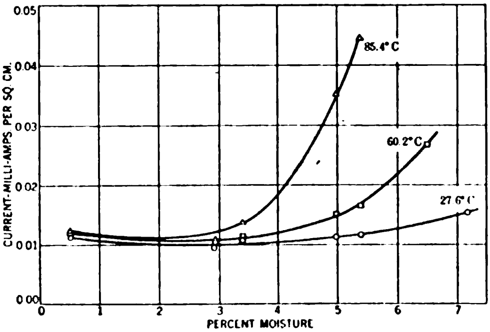


FIG. 26—OIL-TREATED 3/32-IN. PRESSBOARD

Comparative curves showing current vs. per cent moisture at three different temperatures and at 200 volts per mil—60 cycles—sine wave—average thickness of the seven samples was 0.196 in.

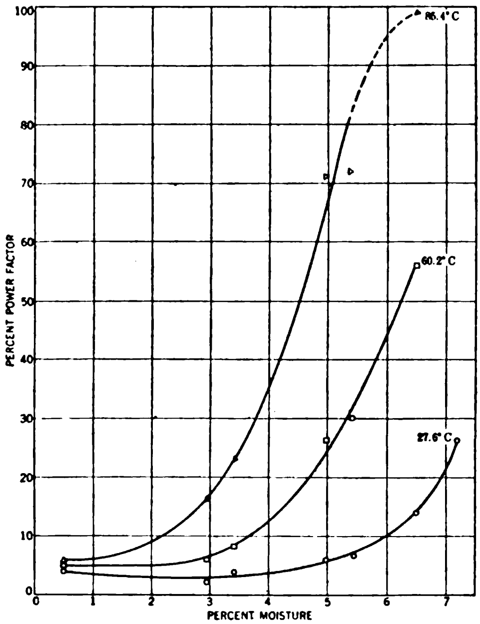


FIG. 27—OIL-TREATED 3/32-IN. PRESSBOARD

Comparative curves showing per cent power factor vs. per cent moisture at three different temperatures and at 200 volts per mil—60 cycles—sine wave—average thickness of the seven samples was 0.196 in.

(*a*) *Voltage Equations.*

1. *Current vs. volts per mil.* It has been found that the current values, I, as given by Figs. 9, 15, 20, and 23, can be expressed as a function of the voltage, V, by the general equation

$$I = K_1 V + K_2 V^n \qquad \textbf{(20)}$$

Ordinarily, at about room temperature and for fairly good insulation, the results can be expressed by the first term of equation (**20**), so that the second term becomes zero. For these cases

$$I = K_1 V \qquad \textbf{(21)}$$

The second term of equation (**20**) represents the deviation from a straight line which is tangent to the curve at the origin. If I is expressed in milliamperes per sq. cm. and V in volts per mil, the following equations express the results nicely:

Fig. 9 Varnished cloth—Sample No. 1—$I = 0.0000497\,V$
" 9— " " — " No. 2—$I = 0.0000465\,V$
" 9— " " " No. 3—$I = 0.0000486\,V$
" 15—Pressboard—Sample No. 1—53 deg. cent.—$I = 0.0000453\,V + 3.1 \times 10^{-16}\,V^{4.65}$
" 15— " — " No. 1—80 deg. cent.—$I = 0.0000458\,V + 2.5 \times 10^{-14}\,V^{3.87}$
" 15— " — " No. 1—103 deg. cent.—$I = 0.0000492\,V + 4.0 \times 10^{-24}\,V^{8.03}$
" 15— " — " No. 1—127 deg. cent.—$I = 0.0000604\,V + ?$
" 20— " — " No. 2—27 deg. cent.—$I = 0.0000567\,V$
" 20— " — " No. 2—60 deg. cent.—$I = 0.0000594\,V$
" 20— " — " No. 2—85 deg. cent.—$I = 0.0000603\,V$
" 23— " — " No. 3—28 deg. cent.—$I = 0.0000577\,V$
" 23— " — " No. 3—60 deg. cent.—$I = 0.0000673\,V + 1.24 \times 10^{-8}\,V^{1.91}$
" 23— " — " No. 3—85 deg. cent.—$I = 0.000111\,V + 6.85 \times 10^{-8}\,V^{1.94}$

Equation (**21**) shows that the current varies directly as the voltage. From the above equations, this is seen to be true with all samples tested at room temperature, and also true for some samples tested at higher temperatures. This means that the admittances of the test samples were constant when this equation was satisfied. In order for the admittance of a piece of insulation to remain constant the capacity and resistance must not change or they must change in such a way as to leave the admittance constant. It is more reasonable to believe that the first condition would be fulfilled rather than the second.

When equation (**21**) fails to represent the current passing through the insulation, then equation (**20**) will do it. When the current is rising faster than the voltage, as indicated by equation (**20**), it means that the insulation is weakening, and implies less satisfactory material than if the weakening effect were not present. It is doubtful if any insulation will prove satisfactory that needs equation (**20**) to represent the current passing through it. The equations tabulated above show that some of them are of the form (**20**) and, in these cases, the material broke down under test, while the others did not puncture. This suggests, therefore, that it is not at all unreasonable to judge the electrical value of an insulation merely by making observations of the current alone. The second term of equation (**20**) represents almost wholly, if not entirely, energy current. Part of the constant term also represent energy current. Pressboard sample No. 3 contained 5.38 per cent moisture, while sample No. 2 contained about 0.5 per cent, and one will notice from the above equations that this extra amount of moisture is responsible for large energy currents because the dielectric losses as previously pointed out, were much larger for the former sample.

2. *Power factor vs. volts per mil.* The power factors, as given by Figs. 11, 17, 21, and 24, can be expressed as a function of the voltage, V, by one of the following forms of equations:

$$P = K \tag{22}$$

$$P = K_1 + K_2 V \tag{23}$$

$$P = K_1 - K_2 V \tag{24}$$

$$P = K_1 - K_2 V^{-n} \tag{25}$$

$$P = K_1 + K_2\, \epsilon^{-av} \tag{26}$$

ϵ is the base of the Naperian logarithms.

If P is the per cent power factor, and V the volts per mil, then the following equations represent the various curves given in the figures referred to above:

Fig. 11—Varnished cloth—Sample No. 1—$P = 21.5$
" 11— " " — " No. 2—$P = 18.2$
" 11— " " — " No. 3—$P = 18.2 + 0.0068\,V$
" 17—Pressboard—Sample No. 1— 53 deg. cent.—$P = 1.7$
" 17— " — " No. 1— 80 deg. cent.—$P = 3.0$
" 17— " — " No. 1—103 deg. cent.—$P = ?$
" 17— " — " No. 1—127 deg. cent.—$P = 22{\cdot}8 - 0.0136\,V$

Fig. 21—	"	—	"	No. 2— 27 deg. cent.—$P = 3.0 + 8.2\epsilon^{-0.00405v}$
" 21—	"	—	"	No. 2—60 deg. cent.—$P = 3.5 + 10.3\epsilon^{-0.00372v}$
" 21—	"	—	"	No. 2—85 deg. cent.—$P = 4.0 + 16.5\epsilon^{-0.00462v}$
" 24—	"	—	"	No. 3—28 deg. cent.—$P = 5.4 + 00585\,V$
" 24—	"	—	"	No. 3—60 deg. cent.—$P = 26.3 + 0.0196\,V$
" 24—	"	—	"	No. 3—85 deg. cent.—$P = 100. - 244.\,V^{-0.428}$

Referring to Fig. 17, it will be seen that no equation is given for the curve at 103 deg. cent. This curve first has an apparent decrease and then an increase of power factor. Curves of this type require a combination of two equations to express them.

The equations which represent the power factor as a function of the voltage are quite varied over the range of condition met with in the tests reported in this paper. The equations hold closely over the range of the tests; some of them cannot hold for low voltages, while others cannot apply for high voltages. They are valuable in so far as they give one an idea of the forms of the equations when the power factors are measured over such wide conditions as were met in these tests. When equation (**22**) holds, the power factor does not change with voltage. From the numerical equations above, it is seen that this equation applied in several cases. Insulation which behaves in this way will prove satisfactory as far as dielectric losses are concerned. Equations (**23**) and (**25**) are for power factors which increase with voltage, and (**24**) and (**26**) are for those which decrease with voltage. The numerical equations given shown that all four of the forms are required to express the results. The particular form of equation which will hold depends on the conditions of the test and on the nature of the insulation. It depends on these two things, because the power factor varies from zero to 100 per cent. In order for an equation to represent the power factor completely, it must be one which has these two limits as its asymptotes. The particular form of equation, then, will be influenced by the position of the power factor with respect to these two limits. Both the conditions of the test and the nature of the insulation determine the value of the power factor, as has already been pointed out.

The power factor changes because the capacity and resistance vary. The results show, therefore, that in some cases these do not change, while in other cases, large variations are observed with voltage. One would think the increase in power

factors is due to heating effects. But the losses always produce heating effects, which are small in many cases, and hence, the power factor should always increase, if it changes at all with voltage. It was pointed out, however, that a surprisingly large decrease in power factor with increasing voltage was observed in the case of well dried oil-treated pressboard. In this case the application of high voltage stresses produces effects, the nature of which is not fully known. Just as mica filings are lined up under the influence of an electric field, so are the water and other movable materials in an insulation influenced. It may be that herein lies the explanation of certain electrical phenomena observed in connection with insulation.

3. *Watts vs. volts per mil.* It is found that in almost all cases the watts (W) can be expressed as a function of the voltage (V) fairly well by the equation

$$W = KV^n \tag{27}$$

Referring to equation (**19**), if the power factor is independent of the voltage and the current directly proportional to it, then W should vary directly as the square of the voltage. This law is frequently assumed to be true and many calculations are made depending on this assumption. The table of equations given below will show that this square law does not hold in many cases. If the power factor increases with increasing voltage and the current varies directly as the voltage or faster than it, then the exponent n in equation (**27**) must be greater than two. The current has not been observed to vary less than the first power of the voltage, but the power factor frequently decreases with increasing voltage. In these cases, the exponent n must be less than two. The following table will show all three of these instances. W is expressed in watts per cu. cm. and V in volts per mil.

Fig. 7—Varnished cloth—Sample No. 1—$W = 4.90 \times 10^{-6}\ V^{1.98}$
" 7— " " —. " No. 2—$W = 4.40 \times 10^{-6}\ V^{1.95}$
" 7— " " — " No. 3—$W = 1.87 \times 10^{-6}\ V^{2.15}$
" 13—Pressboard— Sample No. 1—53 deg. cent.—$W = 0.235 \times 10^{-6}\ V^{2.05}$
" 13— " — " No. 1—80 deg. cent.—$W = 0.665 \times 10^{-6}\ V^{1.97}$
" 13— " — " No. 1—103 deg. cent.—$W = 2.47 \times 10^{-6}\ V^{1.88}$
" 13— " — " No. 1—127 deg. cent.—$W = 9.45 \times 10^{-6}\ V^{1.87}$
" 19— " — " No. 2—27 deg. cent.—$W = 15.6 \times 10^{-6}\ V^{1.47}$
" 19— " — " No. 2—60 deg. cent.—$W = 45.5 \times 10^{-6}\ V^{1.32}$
" 19— " — " No. 2—85 deg. cent.—$W = 52.5 \times 10^{-6}\ V^{1.33}$
" 22— " — " No. 3—28 deg. cent.—$W = 0.210 \times 10^{-6}\ V^{2.27}$
" 22— " — " No. 3—60 deg. cent.—$W = 2.75 \times 10^{-6}\ V^{2.14}$
" 22— " — " No. 3—85 deg. cent.—$W = 3.85 \times 10^{-6}\ V^{2.52}$

This table shows that the losses vary at least from the 1.32 to the 2.52 power of the voltage depending on the condition of the test and on the nature of the insulation. Comparing the current and power factor curves with the corresponding loss curves, it will be observed that the "square" law holds fairly well where it should hold theoretically. When the power factor decreases with increasing voltage and the current varies directly as the voltage it will be noted that the same equation holds but the exponent is considerably less than two. In other cases, on account of the manner in which the current and power factor vary with the voltage, the exponent "n" is considerably greater than two. The samples of pressboard which contained the largest percentage of moisture gave the largest values for "n" while the well dried sample (No. 2) gave the smallest. As has been suggested already, pressboard sample No. 1 probably contained a little more moisture than sample No. 2, and it is seen that the exponent has larger values for the former sample than it has for the latter. In addition to this effect of moisture on the exponent "n", the temperature at which the tests are made, also affects the values of the exponent. In the same way, the moisture and temperature influences the value to be assigned for the constant K.

(b) *Temperature Equations.*

1. *Current vs. temperature.* The curves in Fig. 10 showing the current vs. temperature for varnished cloth can be represented by the equation

$$I = K_1 + K_2 \epsilon^{av} \tag{28}$$

while those for pressboard given in Fig. 16 can be represented by:

$$I = K_1 + K_2 T^n \tag{29}$$

It has already been mentioned that the points for the curves given in Fig. 10 do not form smooth curves, and for this reason, it is doubtful if equation (**28**) would represent the curves if the points were more consistent. It may be said that out of a large number of cases tried, equation (**29**) has been found to hold. For this reason, the latter equation is to be considered as the more probable one, to express the results. The following numerical equations express the results given in Figs. 10 and 16. T is expressed in degrees cent. and I in milliamperes per sq. cm.

Fig. 7—Varnished cloth—Sample No. 1—$I = 0.0085 + 3.1 \times 10^{-5} \epsilon^{0.165T}$
" 7— " " — " No. 2—$I = 0.0084 + 2.2 \times 10^{-5} \epsilon^{0.164T}$
" 7— " " — " No. 3—$I = 0.0084 + 2.7 \times 10^{-5} \epsilon^{0.165T}$
" 16—Pressboard—Sample No. 1—100 VPM—$I = 0.0045 + 5.3 \times 10^{-17} T^{5.95}$
" 16— " — " No. 1—150 VPM—$I = 0.0068 + 1.55 \times 10^{-18} T^{6.75}$
" 16— " — " No. 1—200 VPM—$I = 0.0092 + 7.3 \times 10^{-17} T^{6.00}$
" 16— " — " No. 1—250 VPM—$I = 0.0117 + 1.36 \times 10^{-16} T^{5.95}$

The constant terms in these equations represent that part of the current which does not change with temperature. The second terms, however, are seen to increase rapidly with the temperature. These second terms represent weakening effects in the insulation, which is finally broken down due to them. These terms, then, probably represent almost entirely energy current, which is seen to increase about as the 6th power of the temperature. Consequently, for large values of T the weakening effects increase very rapidly. At low temperatures, the weakening effects are not so of much importance as at the higher temperatures. These same effects are noted for power factors and losses.

2. *Power factor vs. temperature.* Since the current can be represented as some constant plus a term to represent weakening effects, due to increased temperature, it is natural to look for the same kind of a law to represent the power factor as a function of the temperature. Referring to Figs. 12 and 18, it is seen that the shape of the curves is similar to that of the current curves showing the temperature effect. As a matter of fact, if P is the per cent power factor and T the degrees cent. then

$$P = K_1 + K_2 T^n \tag{30}$$

for the curves given in Figs. 12 and 18. The numerical equations for the curves in Fig. 12 on varnished cloth are:

Sample No. 1—$P = 3.5 + 1.20 \times 10^{-9} T^{4.60}$
" No. 2—$P = 3.5 + 1.80 \times 10^{-9} T^{4.45}$
" No. 3—$P = 3.5 + 0.29 \times 10^{-9} T^{4.85}$

The curves shown in Fig. 18 are so nearly the same that the following equation represents an average curve through the points at the various temperatures:

$$P = 1.6 + 1.25 \times 10^{-12} \; T^{5.75}$$

These equations hold nicely over the range tested, but they could not represent a curve extending from 0 to 100 per cent power factor for reasons pointed out in the section dealing with the voltage equations. These equations show that the weakening effects, due to increase of temperature, are causing large increases in the power factors as well as in the magnitude of the currents.

3. *Watts vs. temperature.* It would seem reasonable to multiply the current and power factor equations together at any constant voltage in order to express the watts as a function of the temperature. This would yield the desired equation but since the current and power factor equations are alike for the curves given in this paper, it is to be expected that loss equations will be of the same general form. This expectation is fulfilled for if W is the watts per cu. cm. and T the degrees cent. as before, then

$$W = K_1 + K_2T^n \tag{31}$$

The constant term represents the loss which does not change with temperature, while the second term is accounted for by the weakening effects due to the influence of temperature. The following equations show these effects to increase rapidly with temperature, and the curves in Figs. 8 and 14 represent the results graphically.

Fig. 8—Varnished cloth—Sample No. 1—$W = 0.020 + 6.8 \times 10^{-13} T^{5.15}$
" 8— " " — " No. 2—$W = 0.025 + 3.5 \times 10^{-13} T^{5.25}$
" 8— " " — " No. 3—$W = 0.020 + 9.7 \times 10^{-13} T^{5.10}$
" 14—Pressboard—Sample No. 1—100 *VPM*—$W = 0.0030 + 7.6 \times 10^{-16} T^{6.15}$
" 14— " — " No. 1—150 *VPM*—$W = 0.0060 + 3.1 \times 10^{-14} T^{5.40}$
" 14— " — " No. 1—200 *VPM*—$W = 0.0110 + 1.40 \times 10^{-14} T^{5.70}$
" 14— " — " No. 1—250 " —$W = 0.0150 + 4.8 \times 10^{-9} T^{4.05}$

It should be stated that these equations do not fit the curves exactly, for at the higher temperatures, the equations give too low results. This tends to show that the temperature of the insulation was higher than that actually recorded, thus producing greater losses than indicated by the equations. The energy dissipated in the insulation was sufficient for high dielectric losses to produce considerable heating effects. Now, these high losses occur at high temperatures and the rise of tempera-

ture of the insulation above that of the surrounding oil becomes appreciable only at the higher temperatures, say above 100 deg. cent. If this rise of temperature could have been taken into consideration, then it is probable that equation (**31**) would apply quite closely. Taking into account the deviations of the equations from the experimental curves, they seem to indicate that the rise of temperature of the test pieces above the surrounding oil was probably five or six degrees cent. This increase of temperature occurred during the time the potential was applied, which was not more than a few minutes in most cases.

It is to be noted that exponent n for equation (**31**) is about equal to that for equations (**29**) and (**30**). The weakening effects, then, due to temperature, affect the current, power factor, and loss in the same way and they can be represented by the same general type of equation, thus showing the fundamental nature of the effects due to temperature.

(c) *Moisture Equations.*

1. *Current vs. per cent moisture.* The general shape of the moisture curves shown in Figs. 25, 26, and 27 leads one to suspect that they are of the same nature as the temperature curves and that the same general form of equation ought to apply to both sets. It has been pointed out that there appears to be a noticeable increase in the power factors and losses at the lower voltages (50 *VPM*) for well dried samples of pressboard. At the higher voltages (200 to 250 volts per mil) this increase is not so noticeable as shown in the above figures. Consequently it is impossible for the general form of the temperature equations to apply exactly for moisture. Neglecting this peculiarity and considering the weakening effects due to the presence rather than the absence of moisture, the same general type of equation holds for both the temperature and moisture effects. So that, if X is the per cent moisture absorbed in the pressboard and I the current in milliamperes per sq. cm. then,

$$I = K_1 + K_2 X^n \tag{32}$$

The numerical equations for the curves in Fig. 26 are:

At 27.6 deg. cent.—$I = 0.0101 + 9.0 \times 10^{-8} X^{4.40}$
" 60.2 deg. cent.—$I = 0.0105 + 9.9 \times 10^{-8} X^{5.20}$
" 85.4 deg. cent.—$I = 0.0110 + 30.5 \times 10^{-8} X^{5.60}$

It is to be observed that these equations also show that moisture causes weakening effects in insulation in much the same way

that increase in temperature does. In both cases the values for the exponent n are about the same, showing that weakening effects increase even as great as the 5th or 6th power of the absorbed moisture.

2. *Power factor vs. per cent moisture.* The general form of the equation representing power factor vs. per cent moisture is:

$$P = K_1 + K_2X^n \tag{33}$$

It is seen to be of the form (**32**). It holds only over a limited range, perhaps up to 85 per cent power factor. This shows that the power factor is changing in much the same way the current does. The following equations apply to the curves shown in Fig. 27.

At 27.6 deg. cent.—$P = 3.0 + 1.65 \times 10^{-5} X^{6.00}$
" 60.2 deg. cent.—$P = 4.7 + 3.50 \times 10^{-3} X^{3.90}$
" 85.4 deg. cent.—$P = 6.0 + 3.05 \times 10^{-2} X^{3.30}$

These equations show that the effect of moisture on the power factor is the same as the effect on the current.

3. *Watts vs. per cent moisture.* The same form of equation also applies to the curves showing the dielectric loss vs. per cent moisture. That is,

$$W = K_1 + K_2X^n$$

The same limitations are to be placed upon this equation as were put on equation (**32**). The following equations apply to those curves given in Fig. 25.

At 27.6 deg. cent.—$W = 0.035 + 1.45 \times 10^{-9} X^{8.55}$
" 60.2 deg. cent.—$W = 0.050 + 2.65 \times 10^{-6} X^{5.65}$
" 85.4 deg. cent.—$W = 0.061 + 1.25 \times 10^{-5} X^{6.00}$

These equations show that the losses increase rapidly as the quantity of absorbed moisture increases. All of the moisture equations show clearly the harmful effects produced by it, and it is essential to look closely into this matter in studying insulation, which absorbs moisture.

It may be said of the equations as a whole that the exponent n, and the constants, K_1 and K_2, are greatly affected by the voltage, temperature and moisture conditions. There does not appear, however, to be any definite relation between these quantities and the three variables dealt with in this paper. The equations reveal the fact that the nature of the increased conductivity is the same for both temperature and moisture. This lends strength to the belief that moisture may be responsible

for a large part of the phenomena observed. This is also further strengthened by the fact that the currents, power factors, and losses, increase many fold in the neighborhood of 100 deg. cent. and especially above this temperature. This temperature is a critical point for water at atmospheric pressure, but it would require over 100 deg. cent. to boil water in extremely small capillary tubes such as exist in porous insulation. If the moisture is entrapped in an insulation that is only slightly porous, then it could not be eliminated by evaporation so easily. Consequently, when the temperature of the insulation is, say 125 deg. cent. the moisture may show decided increases in conductivity that do not show up below 100 deg. cent. Since most of the losses are due to the absorbed moisture it is reasonable to believe that they are to a great extent in the moisture itself rather than in the insulation. This means that the temperature-rise occurs in the former before it does in the latter. Not more than 12 cu. cm. of moisture existed in any of the test samples considered in this paper and for this reason the losses could apparently produce marked changes in the insulation. As a matter of fact probably little change took place in the material itself and almost the whole change probably was due to the increased conductivity of the moisture on account of the heating effects within it. It is advisable, therefore, to look carefully into the nature of the foreign material an insulation contains, whether this material be moisture or other harmful substances. The equations show that the weakening effects increase as the 5th or 6th power of the temperature and moisture. So that, if the moisture is present to only a few per cent, these effects become excessive and the increase of temperature magnifies them still more. With such an unstable condition of the insulation as here indicated, it is to be expected that the effective temperature of the insulation, for high losses, will be higher than recorded by a thermometer placed under the oil against the test terminal. For this reason the equations may not hold exactly over the whole range for the various curves. Considering everything, the equations represent the results as well as one can desire. As a whole, the results point to a conductivity of an electrolytic nature.

There are many other things to which attention might be given, but this will not be done in the present paper. It is to be hoped that in a future paper further results of the work on dielectric losses, especially regarding the effect of frequency on them, may be given.

Accuracy of Results. It will be well to devote a short space to the consideration of the accuracy of the results given in this paper. Both the current and voltage can be measured to within one or two per cent, but the largest error is introduced by the measurement of the minor axes, b', of the ellipses on the photographic plates. Referring to the illustrations in plate L, it will be seen that no great difficulty would be encountered in measuring b' for illustrations 3, 4, 5 and 6. The measurement of b' for photographs 1 and 2 might be in error as much as five per cent. If one desires to check the measurements given in the paper for these illustrations, he may do so in order to see how accurate the measurements can be made. Experience in making these measurements will be found valuable. It should be said that the measurements can be made on the originals with a greater precision than on these reproductions. For low power factors, as shown in the first two illustrations, each point for dielectric loss may be in error by $\sqrt{1^2 \times 2^2 + 5^2} = 5.5$ per cent. One, two, and five per cent are used respectively for the errors due to voltage, current, and power factor measurements. When points for a curve are taken it is probably true that a point taken off an average curve will not be in error by more than about 2.5 per cent. Certainly, with the larger power factors this precision can be obtained with the cyclograph. An accuracy of the cyclograph equivalent to this is quite satisfactory for the kind of work to which this apparatus is adapted.

V. Conclusions

The following conclusions are arrived at as a result of this investigation on dielectric losses:

1. The successful application of the cyclograph in determining dielectric losses in insulations is amply demonstrated by the results given in this paper.

2. For good insulation the current should vary directly as the applied voltage. If the current increases more rapidly than this, it will show weakening properties.

3. The dielectric losses vary over wide limits depending on the condition of the tests and the nature of the insulations. The losses show clearly the electrical value of an insulation.

4. The results given in the paper show that the power factor of insulation may vary from about 2 to 99 per cent. The nature of the insulation and the condition of the tests determine its value.

5. It is shown that the watts do not vary as the square of the voltage, but may vary from the 1.32 to the 2.52 power of the voltage.

6. The weakening effects in insulation, as shown by the dielectric losses, power factors, and currents, may increase as great as the 5th or 6th power of the temperature.

7. The weakening effects in pressboard, and very likely other water absorbent insulations, may also increase as great as the 5th or 6th power of the per cent absorbed moisture. When the free moisture is above 3 per cent the weakening effects due to its presence are quite pronounced.

8. Empirical equations are derived that will express the dielectric losses, currents, and power factors, as functions of the voltage, temperature, and absorbed moisture.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

I—Notes on Investigation of Types of Foundations—Digging Holes for Foundations—Concreting Foundations—Erecting Towers

BY J. A. WALLS

ABSTRACT OF PAPER

Concrete tower foundations of mushroom type, requiring no forms or back filling, as used in recent Baltimore-Holtwood transmission line, are found to be cheaper and stronger than steel tripod foundations previously used in a similar line alongside.

It was found that mushroom type concrete foundations could be built with a smaller construction force and at lower cost, and more rapidly, than certain types of concrete foundations requiring forms and back filling.

The procedure of digging holes and concreting of mushroom type foundations is described.

Method of erecting transmission towers by the use of a shear leg is described in some detail.

THE FOLLOWING notes relate to the transmission lines of the Pennsylvania Water & Power Company. On the first Holtwood-Baltimore Line (No. 12) the steel tripod stub, Fig. 1 was used with suspension towers and a concrete foundation, Fig. 2, with anchor towers.

On the Holtwood-Lancaster Line mushroom type concrete foundations were used for both suspension and anchor towers.

Lifting tests made on steel tripod stubs, steel single leg stubs, (with fins at top and bottom Fig. 4) and under-cut mushroom type concrete stubs (the lift being not vertical but inclined, and parallel to the direction of the tower leg, though in service the horizontal component would be somewhat greater than this) showed that the tripod type pulled out of fresh ground at about 32,000 pounds; the single leg at about 23,000 pounds; while the mushroom concrete type showed no signs of lifting or cracking of soil up to the limit of capacity of the testing outfit, *i.e.*, 70,000 pounds. The shifting of the single leg stub was more than one inch at 50 per cent of its ultimate loading; the tripod stub

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movement at 50 per cent ultimate loading was $\frac{1}{4}$ in. in the vertical direction and $\frac{5}{16}$ in. in the lateral direction.

Experience in the field indicated greater difficulty in securing exact setting with the tripod stub than with the concrete stub, so in view of the greater strength of the concrete stub, its lesser liability to displacement when pivoting on it in tower raising, and the consequent lessened chance of unequal stressing of the tower legs, due to lack of fit of the tower shoes with the foundations, together with certain other construction advantages, determined the use of concrete stubs for both suspension and anchor towers on the second Holtwood-Baltimore Line (No. 56). The reason for the massive construction adopted, it should be explained, is that this latter line is a short and important trunk line

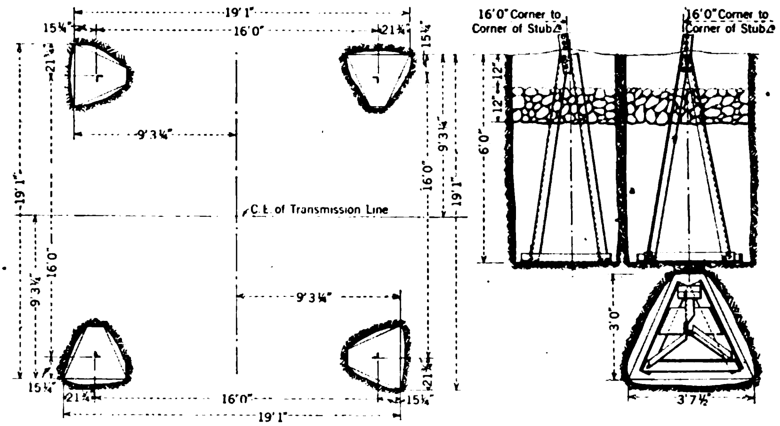

FIG. 1—STEEL TRIPOD TYPE FOUNDATION

of very heavy construction, *i. e.*, 15,000 pounds and 30,000 pounds breast pulls for suspension and anchor towers respectively carrying two circuits of 30,000 kw. per circuit and insulated for 110,000 volts.

Investigations were made on four types of concrete foundations to determine which type of foundation would best suit our conditions. Concreting was done with a hand mixer. The earth was hard red clay with a few small boulders.

The mushroom type, without forms, was constructed by digging a post hole, approximately 16 in. in diameter, 6 ft. in the ground and under-cut at the bottom of the hole as shown in Fig. 3. It was later found advisable to dig the post holes only 3 to 4 ft. deep and make a bell shaped expansion in the bottom by

the use of dynamite. The mushroom type, in good ground, is cheaper to build, can be built more quickly than the other types experimented with, and is especially satisfactory on account of not disturbing the adjacent ground or necessitating backfill.

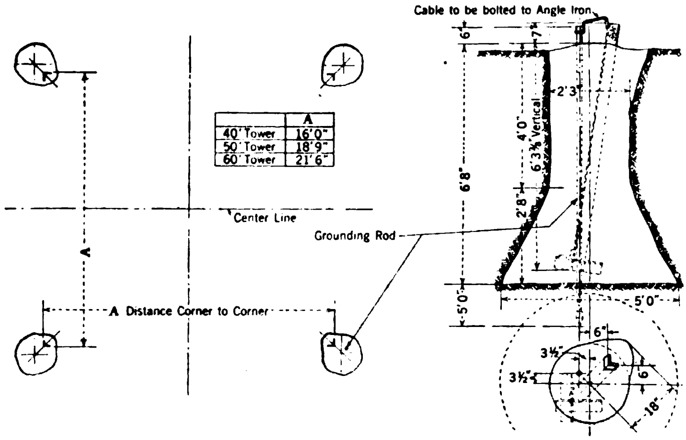

FIG. 2—MUSHROOM TYPE CONCRETE FOUNDATION FOR HEAVY TOWERS

The next best type of foundation appeared to be the mushroom type using steel forms. Considerable difficulty was experienced at the start with the latter type owing to the difficulty

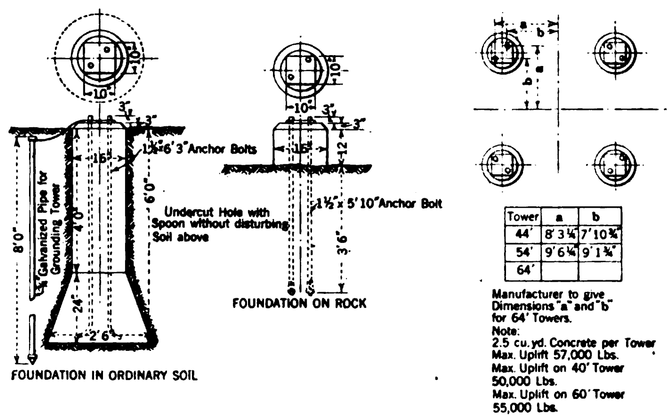

FIG. 3—MUSHROOM TYPE CONCRETE FOUNDATION

of keeping the forms properly lined up and vertical, since the form had a tendency to float and cant when the concrete is poured into it. It was found possible, to prevent this by backfilling slightly before pouring the concrete, the backfilling not

being too much to prevent the withdrawal of the steel forms. In this type and the following types, excavating by dynamite did not prove successful.

Next in order in point of cost and rapidity of construction was the mushroom type with wooden forms. Here 24 sets of forms are required, which are heavy and difficult to assemble.

The least satisfactory type of base was the trunkated pier with wooden forms. This pier had a square base 2 ft. 6 inches each way and a square top 12 in. each way. Like the others it was six feet high. The wooden forms are heavy and hard to assemble in the field, although a little less difficult to assemble than the forms for the preceding type of base. As with the preceding type of foundation, a three days' supply of forms is required for a gang, *i. e.* 24 sets of forms involving, as extra men, a carpenter, a foreman, and three helpers with team to provide steady work for the concrete gang.

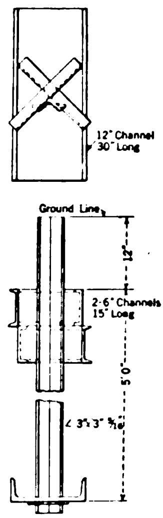

Fig. 4—Steel Single Leg Stub

The type adopted on Transmission Line No. 56 was that shown in Fig. 3 and the actual cost of this type on the line averaged per tower, as follows:

Hauling materials	$13.20
Grading	2.27
Digging	4.92
Materials and concreting	28.50
	$48.89

The type used on Transmission Line No. 12 shown in Figs. 1 and 2, averaged per tower, as follows (3 steel foundations to one concrete foundation):

Hauling materials	$8.03
Grading	4.80
Digging	11.34
Materials and concrete	30.08
	$54.25

Digging Holes

Tools. Each man in the digging gang is provided with the following tools:

1 Long Handle Shovel,
1 Digging spoon with 8 ft. Handle,
1 one inch by 8 ft. telegraph digging bar,
1 Post Hole Digging Bar 6 ft.

PLATE LI.
A. I. E. E.
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ERECTING SHOE [WALLS]

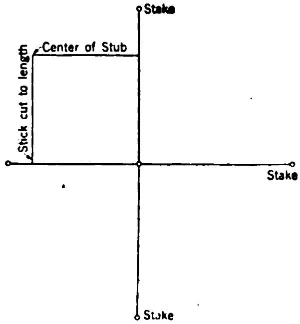
ARRANGEMENT OF HEAD PINS [WALLS]

SIDE GUY TACKLE [WALLS[

The foreman is provided with 40 per cent dynamite, exploders and battery.

The foreman lays out and stakes the center of each hole. In order to avoid the transportation of a templet, the laying out is done as follows:

The engineer stakes the center of the tower and marks the tower height on the reference stake; in addition to this two stakes are put down in the direction of the line and two stakes across the line. These four stakes give the center line of the base. A cord is strung across two of the stakes and the distance from the center stake to a line through the center of two holes on the same side measured by means of a stick cut to length. The point arrived to is marked with a pin and the operation is repeated on the other side of the center. By swinging the cord 90 degrees to the other stakes two more points are located. By laying out two sticks of a length equal to half the base width of the tower from two adjacent points found in the first operation, and then swinging them till their ends meet, the center of one corner is located. The operation is best understood from the accompanying sketch.



In this way two men can lay the base out in less than five minutes and no heavy tools are required. One man is provided for each hole, and the foreman is able to take care of three to four gangs. When a man starts a new hole he first makes a circle, approximately 16 in. diam. around the pin, and the foreman sees to it that he keeps his hole inside this circle.

The hole is dug about three feet deep using the post hole bars to loosen up the soil, and a long handle shovel to scoop it out. If the soil at this depth is too hard to scoop out with a spoon a hole about two feet is punched in the center and the hole shot with about one half stick of dynamite. The dynamite will loosen up the soil and works down and sideways so as to form the bell. After the shooting, the loose dirt is scooped out with a spoon. Under ordinary conditions one man can dig from two to three holes a day in this manner, In some places rock has been encountered. Sometimes this rock is soft enough to be dug out with a bar, in other places it has to be drilled and dynamited. Three to four shots generally opens

the hole. It has been tried to blow holes open with dynamite in the following way:

A hole is punched about four feet deep by means of a bull point and one half stick of 60 per cent dynamite lowered to the bottom of the hole. One half stick of 40 per cent dynamite is suspended in the hole about 8 inches above the bottom stick and another half stick of 40 per cent with a fuse cap about 20 inches from the top. By this method one man has been able to open a hole in 45 minutes, but due to unfavorable soil encountered, this method was not generally followed.

Concreting

The concrete mixture used for the foundations is made in proportions varying from 1:2:4 to 1:3:5. The cement is good quality Portland cement. Test samples taken from various lots show that the cements meet the specifications of the American Society for Testing Materials. Three-quarter-inch stone and sand were shipped in carload lots to various stations along the line. Four head teams were used for hauling the material from the railroad stations, each team being capable of hauling from $\frac{3}{4}$ yard on bad roads to 1.5 yards on good roads. The distribution was kept well ahead of the concreting gang, 1.5 yards of stone and 3.4 yards of sand being dumped at each tower site. This amount was increased about 50 per cent at every fifth tower, so as to make up for occasional shortages. The cement was delivered in bags, and had to be distributed as the work proceeded. In most cases no storage room was available at the railroad stations and, therefore, the cement had to be stored in farmer's barns along the line, 100 to 200 bags being stored at each place. A team following the concreting gang could pick up the cement at these barns and could distribute the bags directly ahead of the work. This procedure kept the loss due to wet weather at a minimum.

The equipment for a gang of men engaged in transmission line work must necessarily be made as light as possible on account of the small amount of work to be done at each place. This is especially true of the concreting gang, as those men invariably spend more time in moving than in concreting.

The time required for mixing and pouring the concrete is about three quarters of an hour, while moving and setting up takes about one hour. The move from tower No. 312 to No. 313 at Big Gun Powder crossing may be given as an ex-

aggerated example of the time required for moving. The teams had to make a detour of about five miles at this place and it required eight hours to move the concreting outfit between the two towers, a distance of 1100 feet.

A 2.5-cu. ft. hand mixer had done excellent work on the Lancaster transmission line and such a mixer was, therefore, purchased for the work on line No. 56. This mixer runs on two wheels and weighs about 1000 lb. with loading platform. The wheels are provided with separate axles and a few days work showed the necessity of strengthening these axles, which was done with a heavy flatiron strap on each side of the mixer. This mixer is still in good condition after being hauled 40 miles over rough ground. Water was hauled in a steel tank mounted on a two horse wagon. The tank was made of $\frac{1}{4}$-in. steel plate, which proved to be unnecessarily heavy.

Water was taken from small streams and creeks and was drawn up by means of a 4-in. boat pump. A more efficient way would be to mount a small lever suction pump equipped with 10 to 15 feet of hose on the tank wagon. With such a pump the water could be reached without driving the wagon too close to the soft banks of the stream.

Smaller tools needed by the concreting gang are:

4 wheelbarrows
4 concrete buckets
4 barrels for water
2 digging spoons
3 shovels
1 digging bar
1 concrete chute for the mixer
1 level board
1 24-in. carpenters level
1 cross cut saw
1 maul hammer
1 set of carpenters tools

In addition to this, a small amount of blocking and running boards must be carried.

The smallest number of men needed for efficient handling of this work is one foreman with nine men, with from one to three teams depending on the length of haul of water and cement. The men would be distributed as follows:

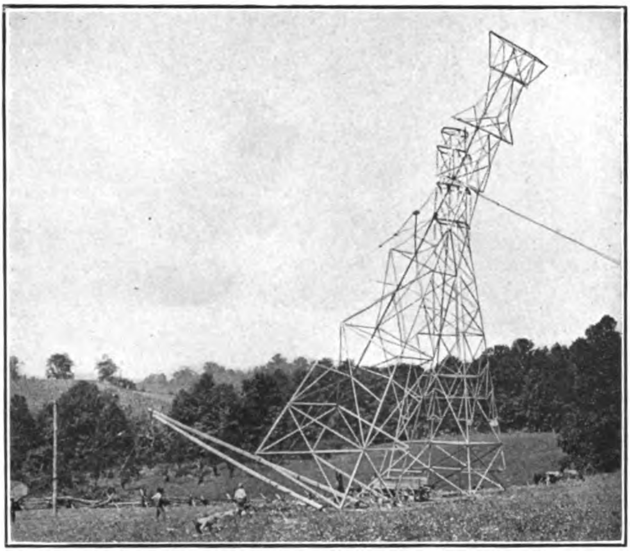
One man wheeling stone
" " " sand
Two men wheeling concrete

One man hauling water and cement
Two men turning mixer
One man loading wheelbarrow with concrete
One man tamping
The teams hauling water, cement and assisting in moving.

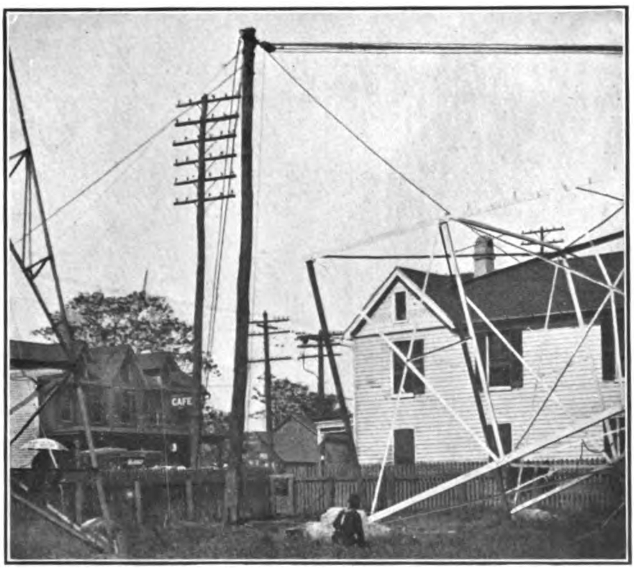
Two or three additional men can and have been used to advantage in this gang. When placing concrete these additional men seem unnecessary being mostly occupied with loading sand and stone in wheel-barrows and bailing water from one barrel to another, this latter operation being necessary on account of the difficulty in moving the water wagon or a full barrel. The real benefit of these men is, however, shown when moving. Let us consider, a case where two teams are available for moving. As soon as the last batch of concrete is mixed a number of men will start loading the tools on the wagon. But before this, two men have been sent ahead to set the forms and place supports for the templet. Ten men are needed to move the templet and this leaves one man in a gang of thirteen to help the teamsters clean up the place and unload at the next tower. At the new set up the foreman will use four men or five men in lining up the templet. One man handles the level board and four men move and block up the templet in position and then place the anchor bolts. In the meantime the other men have completed the unloading, blocked up the mixer to such a height to permit a wheelbarrow to be placed under the chute and laid out the running board so as to make everything ready for the placing of concrete.

With only one team available, two trips must be made for the tools, and with a smaller number of men, one part of the job must wait for the other. It is, however, to be noted that the records do not show any saving in money, but the speed is increased. Naturally the larger gang will make a better showing in rough country where the moving is hard, than on a level stretch with good going. Two men and a team were sent back occasionally to strip forms, bringing them ahead, distributing them where needed.

Originally buckets were used for removing the concrete from the mixer, but this proved to be inefficient as concrete could be mixed faster than it could be removed. A portable inclined runway was, therefore, made by means of which the mixer could be elevated enough to permit the placing of a wheelbarrow under the chute. When water was found in the



BACK GUY TAKING WEIGHT [WALLS]



ERECTING TOWER WITH GIN POLE RIG [WALLS]

holes it was removed with a boat pump. This worked all right in such places where the holes filled slowly, but in a few instances the water would fill in very fast and the holes could not be kept dry. It would be well to carry a short length of six-in. sheet iron pipe for such cases. The concrete could then be poured through the pipe without draining the holes and there would be no chance for the water to wash the cement out of the mixture. At the last end of the job a broken boat pump was used for this.

No bed plates were on the job when the work was started, and it was, therefore, tried to finish the first group of piers with help of dummy plates. This proved to be a very slow process and did not provide a very good seat for the plates. The dummies were then abandoned and until the plates arrived, piers were left about eight inches below the final grade. As soon as the plates arrived, an instrument man with his rod man and one laborer were sent back to finish the foundations, the bond between new and old concrete being obtained by means of toxement.

When bedplates are on hand at time of making the piers, the concrete is poured to within an inch of the top of the bolts and the instrument man gets his grade by hammering the plates down in the soft concrete, and is relieved from carrying cement and mixing concrete.

All material used for concreting during cold weather was heated, the piers were built up to ground line only and covered with sand to prevent freezing. When warm weather arrived men were sent back to finish these piers.

Erecting Towers

Whenever possible the towers are assembled on the ground in a horizontal position. A rigging gang follows the assemblers and erects the towers. This rigging gang consists of a foreman with 11 men and a four-head mule team. The general scheme of erection is to pivot the lower tower legs to the foundations and then lift the head of the tower by means of a tackle running from a point below the cross arms over a shear leg to a dead end at a convenient distance ahead of the tower. The lifting is done by hitching the mule team to the lead line.

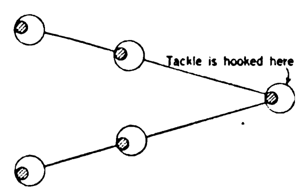
Dead Ends. In average soil the dead end consists of heavy iron pins, 2.5 in. diam., about 5 ft. long. Five of these pins are used for the main tackle, three for the back guy, and one

for the side guy. The pins are driven about three feet apart and connected with a chain, as shown in the accompanying sketch. The tackle is hooked in the front edge of the wedge.

Tackle. The main tackle consists of two 12 in. three-sheave blocks reeved with 600 ft of 1.25-in. hemp rope. Both the side and the back guy tackles consist of 8-in. two-sheave blocks reeved with $\frac{3}{4}$-in. rope. The side guy tackle need only be a short one, but the back guy tackle is of the same length as the main, so as to reach out to the shear leg.

Shear Leg. The shear leg is made of two 45-ft. spruce timbers, measuring about six in. at the top. The height of the lift is less than 43 feet as the timbers are bolted two feet from the top and the butts are spread about 16 feet. The pole tops are shod on both sides with heavy steel plates, so as to prevent splitting. The butts are grooved for kick lines.

Pivots. The light section 40-ft. towers are pivoted on a $\frac{5}{8}$-in. case hardened machine bolt on each side, the bolts running through the leg angle and standard foundation shoe. One tower was dropped and slightly damaged on account of a faulty foundation shoe breaking. This led to the ordering of one pair of shoes made of extra heavy angles and of such a height that the tower leg cleared the foundation plate by more than $\frac{1}{2}$ in., while the tower was being raised.



All extension and heavy towers are bolted to a hinge turning on a 1.25-in. bolt. The hinge and bolt are supported by means of a $\frac{3}{4}$-in. plate bent in channel shape with the web resting on the foundation.

Setting up Rigging. Two men each at the main lift and back guy select a spot in line with the tower and drive their pins for the dead ends. Twenty pounds sledge hammers are used for driving the pins. If the ground is too soft to hold the pins, a dead man is buried. One man rigs up the side guy, two men put the shear leg in place, fix the kick lines and fit the shoes on the tower, while two more men put spreaders between the tower legs and attach the chains for the lifting tackle and a sling for the back guy. The main lift is hooked to the corner angles at the point where the braces in the first and second panel below the cross arm meet. This brings almost the full weight of the tower on the tackle. It was found un-

necessary to use any spreaders in the chains. The spreaders used in the tower legs consist of two by four-inch green oak bolted together so as to form four by four-inch. Two pieces bolted together make a more elastic strut, less liable to break if it falls down.

Lifting Shear Leg. With pins driven, shoes fitted, and the shear leg in place, everything is ready to lift the shear leg. A wooden cross piece, usually four by four inches, is placed over the upper tower legs so as to give the shear leg a start. The back guy tackle is hooked to a wire cable, running over the cross piece to the top of the shear leg and a pair of mules in the lead line lift the shear leg with main tackle and all. The main tackle is used for steadying the rig as the lifting cable is made to such a length that the shear leg must be pulled a little ahead before the chains can be hooked. The block of the main tackle is placed right at the top of the poles. As soon as the chains are hooked the tackle is slacked back and unhooked. The wire cable used for this lift is then lashed to the tower, so as to prevent the shear leg from falling when the main tackle lets go. Lifting the shear leg this way, besides being the most convenient method, gives a good test on the pins in the back guy.

Hoisting Tower. The shear leg being up and all rigging in place, the four-head mule team is hitched to the main lead line. Two men are stationed at each set of pins and no strain is taken before these men have reported everything o. k. On the first start the team goes just far enough to put full stress on the pins, and then stops. If everything proves all right, the team is ordered ahead and proceeds slowly until the men at the back guy commence to feel the weight of the tower on their tackle, when the team is stopped. This is the most critical point of the erection as the tackles on both sides of the tower must be kept taut. In case of a line fouling, one step too many by the team, is liable to pull the pins out or break a tackle, and the tower will fall. The team is, therefore, moved a step at a time only, at this stage until the weight of the shear leg is sufficient to pull the tower over when the team is unhitched and the tower let down with the back guy alone. The front leg being about six inches from the foundation, the tower is held until the spreaders are moved and one foundation shoe fitted to each side. When the tower is lowered the remaining six inches, these shoes are guided over the foundation bolts. In case the

special erecting shoe is used the tower is rocked ahead by means of the main tackle and these shoes exchanged for standard ones.

The side guy is used for emergency only, and is kept taut enough to take out the slack while the tower is going up, but it is not allowed to take any stress. In case something breaks this guy prevents the tower from falling onto line No. 12.

Moving. As soon as the main tackle is unhooked it is stretched by the team so as to be ready for the next lift. The tackle being stretched, a chain is slung around the shear leg and the team drags it to the next tower. In the meantime, the respective men coil up their tackles and load them on a wagon, together with pins, hammers, spreaders, and the like. While this is being done, one man has put all the foundation shoes on the tower with one bolt in each shoe. The final bolting up of these shoes is done by two men behind the rigging gang and counted as members of the same crew.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

II—Transmission Tower Steel Anchors Set in Earth

BY J. B. LEEPER

Abstract of Paper

As tower anchors have been somewhat overlooked causing in some instances much loss, these notes are written to call attention to the importance of properly designing them so that the maximum strength of tower may be obtained with the most economical outlay. The notes show:

1. A method of figuring the loads to be resisted by the anchors.
2. The importance of resisting the horizontal as well as the vertical loads.
3. The effect of the shape of the anchor on strength of tower.
4. Various types commonly used.
5. The economy of the use of an all-steel anchor.

THE ABILITY of a tower to resist the loads coming on it depends largely on properly designed anchors and it is the intent of the following notes to call attention to this fact.

A large percentage of the loads on a tower or pole, are in a horizontal direction, and are applied thereto near the top, causing an effect of overturning at the base. This overturning moment, together with the load causing it, must be taken up by the anchorage.

To illustrate; let Figs. 1, 2 and 3 represent wide base towers having separate anchors for each leg. Fig. 1 illustrates a tower in which the leg angles extended would intersect at or near the resultant of the applied loads. Fig. 2 represents a tower with parallel legs where the bracing carries all the horizontal loads, while, Fig. 3 shows a tower with legs battered so that part of the horizontal forces are carried down through the legs and part by the bracing.

Let A represent a horizontal force applied to the tower at height X from the base, then the anchors must resist a horizontal force equal to A, and a moment equal to AX. If Y equals the distance apart of anchors, then $\frac{AX}{Y} = B$, or the

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vertical load on each anchor due to force A, force B acting downward on one anchor and upward on the other; the horizontal force A being divided equally between the two anchors if the tower is built as shown in Fig. 1. If built as shown in Fig. 2, it is all taken up by the tension anchor, while if built as shown in Fig. 3, the tension anchor takes the same amount as the compression anchor plus the shear carried down by brace Z. If horizontal strut W is used on towers of Figs. 2 and 3 the anchors will each carry one-half of load A, as for Fig. 1.

In designing the anchors both the horizontal and vertical loads must be kept in mind, and as illustrated above, the position of the loads, together with the shape of the tower, will determine the amount of each.

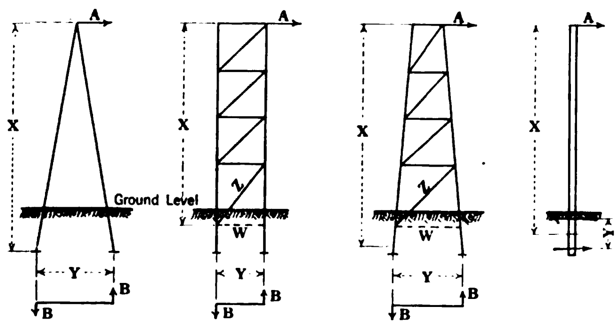


FIG. 1 FIG. 2 FIG. 3 FIG. 4

To resist the vertical load on the anchor is a comparatively easy matter and is usually done by extending the leg of the tower down into the ground to a steel or concrete base.

On account of the variability of the character of the earth and the uniformity of the material in the towers, it seems that the anchors should be designed for a greater possible overload than the towers. How much greater is a question of judgment only.

In designing the anchors to take the uplift we assume the weight of earth at 100 lb. per cu. ft. and that of concrete at 150 lb. In case of an all-steel anchor we figure the weight of an inverted frustum of a pyramid whose sides incline at an angle of 30 deg. with the vertical, assuming this to be the ultimate resistance of the anchor. From the results of some of our tests it seems that these assumptions will give no allowable overload with freshly tamped earth, (see report of tests appended). We have made no tests on anchors after they have

REPORT OF TESTS ON STEEL ANCHORS

Showing Movement Due to Loads Applied to Towers

Test No.	Dist. A	Base	Uplift Thou. lb.	Comp Thou. lb.	Vert. Move't. inches Up-ward	Vert. Move't. inches Down-ward	Horz. Move't Top of Stub Ten-sion	Horz. Move't Top of Stub Comp.	Time set before Test	
1	7′ 6″	30″ Sqr.	24.8 37.2 49.6 64.6	24.8 37.2 49.6 64.6	1.44 4.00 7.00 7.25	.31 .56 1.06			5 mo.	"A" Frame Bolts failed in conn. of stub to leg. 4-23-13
2	7′ 6″	30″ Sqr.	24.8 37.2 49.6 53.4	24.8 37.2 49.6 53.4	.37 1.13 3.00	1.00 1.63 2.50			2 mo.	"A" Frame Comp. stub buckled 5-15-13
3	6′ 0″	10″ × 30″	7.4 14.9 19.3	7.4 14.9 19.3	.25 1.87	.25 .75			3 mo.	"A" Frame Anchor pulled up. 4-23-13
4	7′ 6″	30″ Sqr.	5.7 11.1 16.5 21.9 26.6 42.0	15.7 21.1 26.5 31.9 36.6 52.0	.06 .56 1.31 2.31 4.06	.44 .44 .81 1.00 1.19	Not R	ecorde	d 6 wk.	Tower A Tower failed in lower panel due to movement of Anchors Horz. and vertical. 7-1-13
5	7′ 0″	30″ Sqr.	1.60 31.2 36.6		.31 .75	.31 .94 1.06				Tower A 1. Tower failed by shear of bolts about halfway up the tower. 9-15-13
6	10′ 0″	60″ × 72″	40.0 60.9 81.9 102.8 107.7	45.6 67.5 89.3 111.2 116.3	.13 1.06 2.62 4.69 5.56	.06 .25 .50 .75	+1.25 .... +3.00	−.44	—	Tower B. Tower failed in lower bay due to movement of anchors. 10-14-13
7	10′ 0″	60″ × 72″	39.1 60.7 82.2 103.7 121.6 135.4	46.9 68.5 90.0 111.5 129.4 143.2	.13 .31 .56 .87 1.13	.13 .31 .44 .62 .69	+ .25 + .50	−.13 −.50	12 da.	Tower B. Tower failed in bottom bay. 12-12-13
8	10′ 0″	60″ × 72″	39.1 60.7 82.2 103.7 121.6 136.8	46.9 68.5 90.0 111.5 129.4 144.6	.13 .37 .62 .94 1.25 1.50	.19 .25 .37 .50 .62 .69	+ .25 + .75	−.13 −.13	4 wk.	Tower B Tower not tested to destruction. 12-22-13
9	9′ 0″	48″ × 60″	41.2 56.4 80.0 100.0 112.7	45.2 60.4 84.0 104.6 116.7	.31 .50 1.00 1.87	.25 .44 .75 .94	+ .25	− .0	3 wk.	Tower C. Tower leg failed in lower panel 12-5-13
10	7′ 6″	30″ Sqr.	31.0 36.0 40.0	36.0 41.0 45.0	.62 1.00 1.19	.50 .81 1.00	+ .25 + .25 + .37	.0 .0 .0	2 wk.	Tower C. Tower leg failed in lower panel. 7-16-14
11	7′ 0″	30″ Sqr.	26.3 34.1 41.0	29.7 37.5 44.5	.44 .75	.50 .75	+ .13 + .13	.0 .0	2 da.	Tower E. Tower failed near top. 8-28-14

Tests 1, 2 and 3 were made with "A" Frames.
Tests 4 to 11 inclusive were made with 4 legged Towers.
Style of anchor for tests 1 to 4 incl. and 5 to 9 incl. similar to Fig. 9.
Style of anchor for tests 5, 10 and 11 similar to Fig. 8.
Bases of all anchors were in form of grillage except No. 3 which was $2L^s$ *b* to *b*.
Distance A above is depth of grillage from ground level.

been set long enough for the earth to have settled in the hole and become bonded with the surrounding earth. The tests we have made show that the earth in the hole moves up without disturbing the surrounding earth. It would be very interesting to test some anchors for the uplift after all settlement has been completed, although a transmission line is usually in operation long before the earth has settled completely.

We have found that, although the load on the anchor of the compression side is somewhat greater than the uplift, the governing feature is the uplift, and that if the latter is properly cared for there will be practically no movement downward on the compression side, the anchors for each leg being made alike.

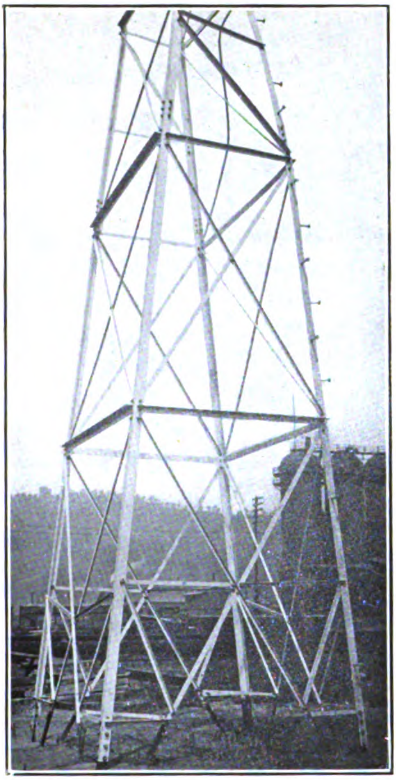
To resist the horizontal force is also a simple matter if the tower is so constructed that all the horizontal shear is taken up in the legs, as would be the case in the tower of Fig. 1, but on account of the necessary separation of wires and other conditions it is usually more economical to use construction illustrated by Figs. 2 and 3. In Fig. 2 all the horizontal force must be taken care of near the surface of the ground, but in Fig. 3 due to the batter in the legs, a part of it is taken by them directly to the base, the remainder must be taken care of near the surface of the ground.

It may be proper to note here that the failure of many towers has been due, at least in part, to the fact that proper provision was not made for this horizontal force.

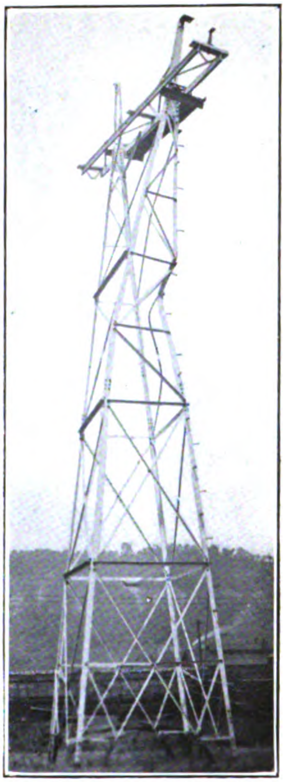
The most of the failures of which I have reports have occurred on towers with anchors as shown in Fig. 6 with concrete omitted, which is a very common type. With this type there is very little resistance to the horizontal component of the stress in the bottom diagonal. The consequent horizontal movement of the main body of the tower causes buckling in the compression leg. A horizontal strut near the ground level preserves the shape of the tower, but tends to cause buckling in the compression stub and also is generally more expensive than the use of anchors of Figs. 7 and 8. This type may, however, be used if care be taken in the design of the tower to see that there is a small stress in the bottom diagonal.

There are several effective methods used in constructing anchors to resist this horizontal force, such as illustrated in Figs. 5 to 8 inclusive.

Fig. 5 shows an all-concrete anchor to which the tower leg is held by means of anchor bolts.



[LEEPER]



[LEEPER]

SHOWING FAILURE OF TOWERS

TOWER FOOTINGS [LEEPER]

Fig. 6 shows a combination of concrete and steel, the leg extending down into the concrete with lugs at the bottom to give bearing on the concrete; the legs being spliced a little above the top.

Fig. 7 shows an all steel design, using four battered angles extending from a point slightly above the ground level to a base at the bottom. It resists the vertical load by means of a system of angles around the bottom as shown, and the horizontal force by the batter of the upright angles. The objection to this type is that it must have a perfectly flat bottom on which to rest, or unequal stresses will exist in the different legs of the anchor. This design is in use on the Big Creek Line of the Pacific Light and Power Company, and others, and although somewhat expensive on account of its weight

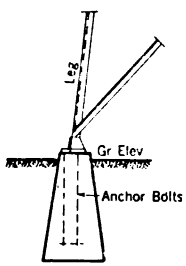


FIG. 5—SHOWING CONCRETE FOOTING WITH ANCHOR BOLTS FOR ATTACHING THE LOWER LEG

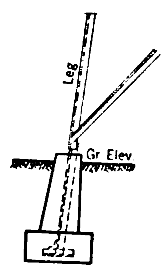


FIG. 6—SHOWING CONCRETE FOOTING WITH LEG ANGLE ATTACHED TO STUB ANGLE WHICH EXTENDS INTO THE CONCRETE

and character of shop work, should prove very satisfactory if properly set. There are other anchors of this type but this seems to be the best, everything considered.

Fig. 8 shows an all steel anchor which has proved very satisfactory, and as far as I know, the least expensive anchor of efficient design that has yet been constructed. In this anchor as shown, the vertical force and part of the horizontal force is communicated through the single stub angle to a steel grillage, the balance of the horizontal force being taken up about two ft. below the ground level by extending the bottom diagonal of the tower down to the stub angle at that point, where a channel or plate of sufficient area is placed to resist most of the load. This style of an anchor has several advantages:

1. The leg splice to the stub can be kept far enough above ground to be out of the zone of serious corrosion.

2. It can be made practically permanent by splicing the stub about three ft. below the ground, making it possible to renew the part of the anchor at the ground level with small expense.

3. Ease of setting, back filling and tamping properly.

4. Small amount of steel necessary and inexpensive shopwork.

The accompanying photographs illustrate the ability of this style of anchor to resist all the loads which are applied to it. In each test that has been made on towers set on these anchors the break has been due to other causes than the movement of anchors.

In this connection I wish to state that we have very few

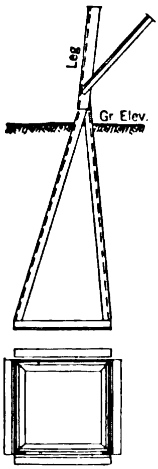


FIG. 7—SHOWING ALL-STEEL FOOTING FOR EARTH SETTING

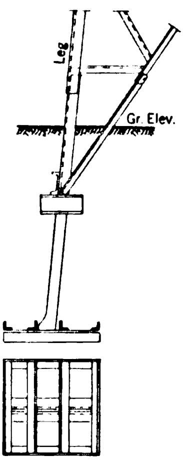


FIG. 8—ALL-STEEL FOOTING FOR EARTH SETTING

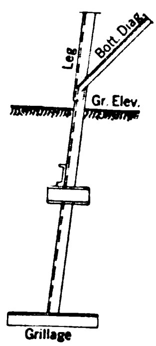


FIG. 9—ALL-STEEL FOOTING WITH HORIZONTAL FORCE IN BOTTOM DIAGONAL NOT PROPERLY PROVIDED FOR

definite data, secured from actual tests, which show the effect of the applied loads on the anchors and towers when taken together. I think this is due to the fact that engineers when specifying their tests do not state clearly how the tests are to be made and as a result the towers to be tested have been set on a rigid foundation, which does not show how the tower would act on its foundation in the field, unless they are to be rigid.

This fact was shown about two years ago when some tests were being made under the direction of Mr. Mershon on some towers for the Inawashiro Hydro Electric Power Company. These towers and their anchors were made as shown in Fig. 9. The bottom diagonal of the tower is attached to the leg of

tower above ground. We found that the tower always failed in the bottom panel when set on its own anchors, but might fail anywhere if tested on a rigid foundation.

In general anchors should be stable, permanent and economical.

Concrete anchors are stable and permanent, but in most cases will be found too expensive and sometimes their cost is prohibitive.

Steel anchors, if properly designed and set, can be made practically as permanent as concrete and are much less expensive.

It should be remembered that there are parts of a tower that may fail without causing complete collapse of the tower, but the anchors are not among these parts.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

III—THE ALABAMA POWER CO.

BY W. E. MITCHELL

ABSTRACT OF PAPER

The development of the type of all-steel tower footing used by the Alabama Power Company for their 110,000-volt double-circuit steel tower transmission lines is outlined with a summary of the conditions influencing the designs finally arrived at.

IT HAS BEEN the writer's opinion for some years that concrete foundations for steel transmission line towers in most sections of the country were not warranted. Due to the inaccessibility of most lines and the impossibility of finding proper concrete materials near them, the cost of concrete foundations, including excavation, frequently runs above $100 per tower and seldom goes below $50.

At the start of the development of the Alabama Power Company a careful investigation was made of the general territory through which the lines were to run with particular reference to railroad and wagon road facilities and concrete materials. It was found the roads were bad and hauls of from four to ten miles from the nearest railway stations were frequent. It was also found that while all lines ran through country with a good clay or disintegrated rock soil, there was practically no sand, gravel or hard rock available for concrete. Studies were therefore made of all-steel foundations and the first 1000 towers were supplied with footings as shown in Fig. 1.

The towers were designed for two circuits of No. 00 seven-strand medium hard drawn copper and two $\frac{3}{8}$-in. Siemen's Martin ground wires. The average span was figured as 750 ft. and maximum span 1000 ft. Minimum ground clearance for conductors 25 ft. The loadings used were eight pounds per square foot of projected area of conductors and sixteen pounds per square foot on flat surfaces. Ice loading was taken as $\frac{1}{4}$ in.,

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as in the section the development is in, sleet is practically unknown. Temperature variation 100 deg. fahr.

The test loads on the towers were:

No. 1 A horizontal pull in direction of line of 3000 lb. at any insulator or ground wire support.

No. 2. A vertical load of 1200 lb. at end of any one or all cross arms.

No. 3. A horizontal pull, transverse with line, of 5000 lb. applied at middle conductor cross arm on center line of tower and at the same time a load of 7000 lb. parallel with line, applied at the top conductor cross arm on center line of tower.

Specifications for tower material were:

Material: A. R. E. Association. O. H. structural steel.

Unit Stresses: Tension, 25,000 lb. per sq. in.

$$\text{Compression,}\ \frac{25000}{l + \dfrac{l^2}{18000\,r^2}}$$

Bolts; Shear, 20,000 lb. per sq. in.

Bearing, 40,000 lb. per sq. in.

All material galvanized, except bolts to be sherardized.

Connection bolts, $\frac{1}{2}$ in. diameter. Ladder bolts $\frac{5}{8}$ in. diameter.

Anchorage connection bolts, $\frac{5}{8}$ in. diameter.

With the above data for designing the towers proper, the design of the footings was arrived at as follows:

Experiments with buried disks and other flat plates show that in pulling them up the soil is removed in the form of a cone and that the angle of the sides of the cone very closely approximates the adherence angle of the soil. In determining upon the size of the footing and the depth to which it should be put, it was assumed that the maximum force withstanding tension in the tower stub was the weight of an inverted truncated cone of earth which had the area of the tower footing as the smaller base and sloped outwardly at an angle of 30 deg. from the vertical. The weight of the soil was assumed as 100 pounds per cubic foot. In this calculation no account was taken of the unknown but ever present friction between the soil in the cone and the surrounding soil.

To withstand a thrust on the footing, a fair bearing pressure per square foot was assumed. By these calculations it was found that a base about 6.25 square feet in area and buried 7.5 feet in

the earth would give a factor of safety of two. The lightest grillage for this given strength therefore was 2.5 feet square.

In the field work it was found that it was necessary to dig a hole at least 2.5 feet by 3.5 or 4 feet in order to allow the men sufficient room in which to work. It was evident therefore that an anchor of rectangular shape would require less excavation and for that reason the later towers were ordered with anchors

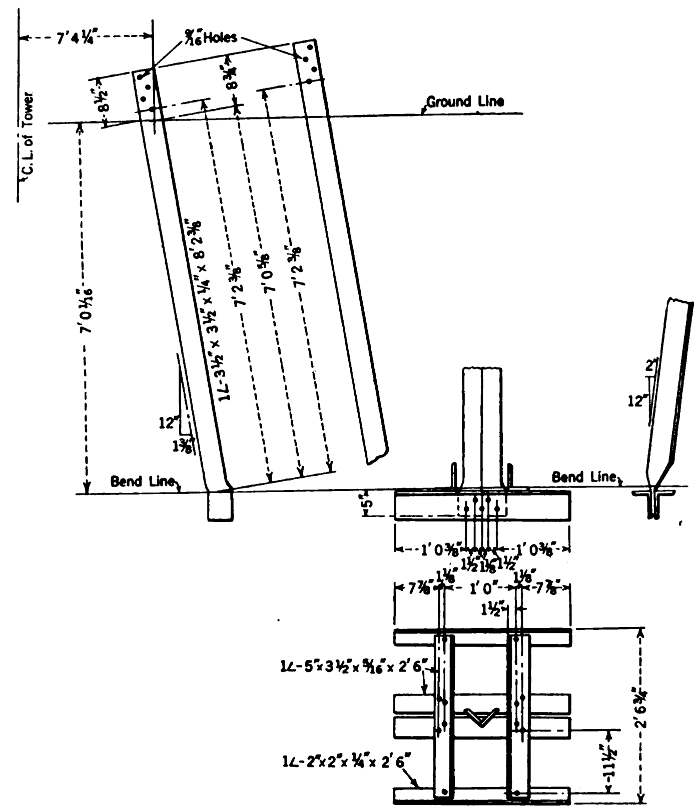


FIG. 1—FOOTING FOR TYPE "A" TOWERS

2 feet by 3.5 feet in area. The grillage weighed more but the saving in field work more than off-set the greater cost of metal.

In tests and in the field where the erected towers were subjected to heavy overturning strains, it had been noticed that the legs tended to move toward each other at the ground line, showing that the earth, though well tamped around the stub, would yield to the horizontal stress in the lowest diagonal. At this

point the tower leg must resist a force at right angles to its loading, and this force acts upon a very long lever beam. To care for this force, it was decided to make the point of junction of the lowest diagonal and the tower leg, about 2.5 feet below the ground

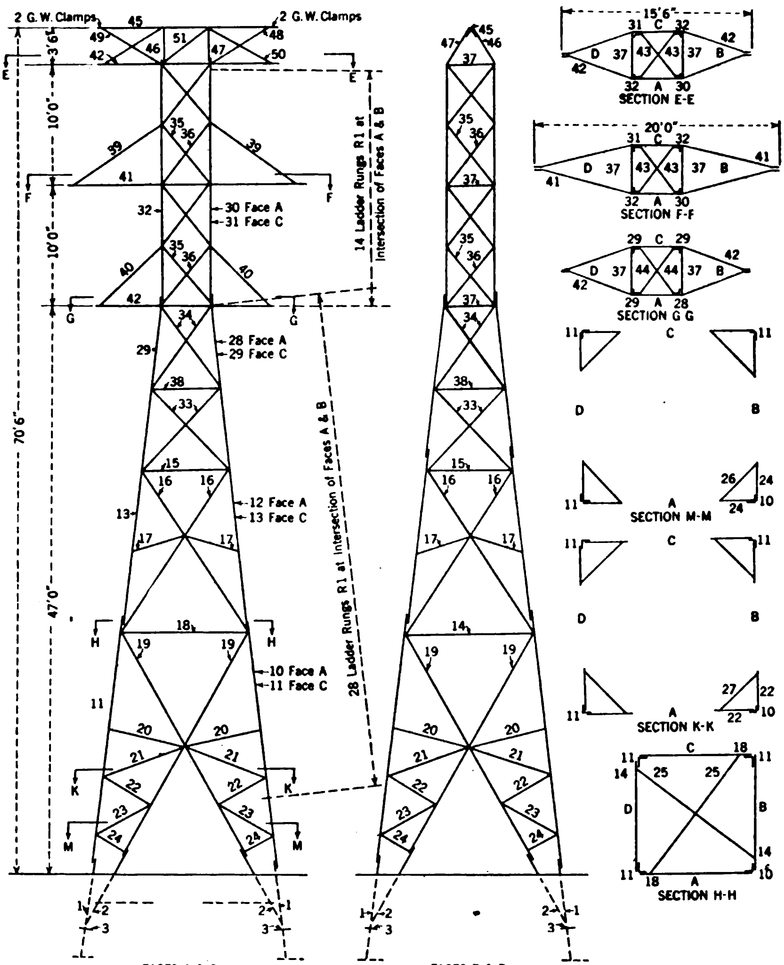


FIG. 2—ERECTION DIAGRAM

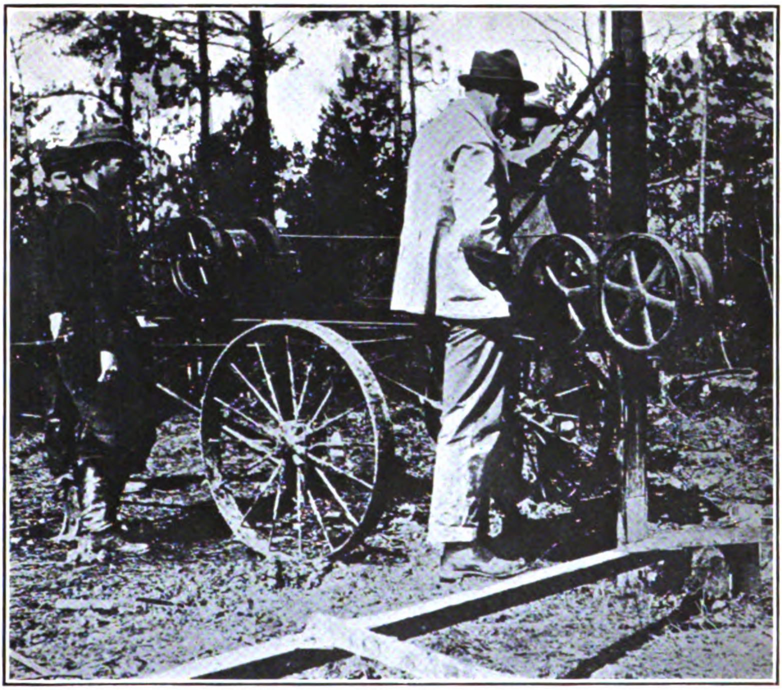
line and there put in some horizontal resisting surfaces. These latter were made of two pieces of 6-in. channel 18 in. long bolted to the leg at right angles to each other. A tower with these modifications of the footings and lower diagonals was tested to destruction. The bolts in the upper part of the tower, as shown

"A" TOWER FOOTINGS [MITCHELL]

SETTING FOOTINGS [MITCHELL]

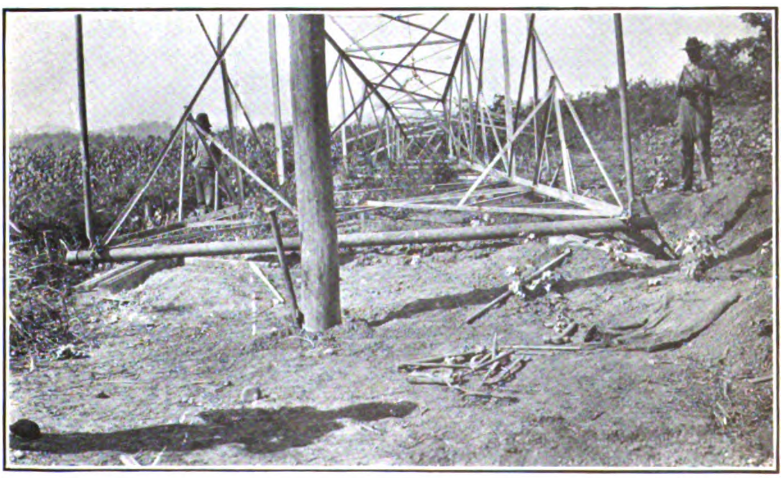
GASOLINE AIR COMPRESSOR AND JACK HAMMER DRILL [MITCHELL]

ROCK ANCHOR [MITCHELL]



[MITCHELL]

GASOLINE TAMPER



[MITCHELL]

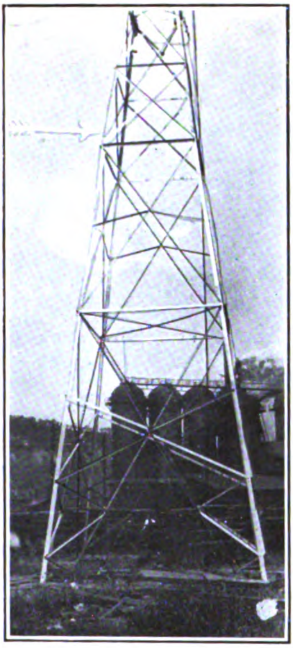
TOWER READY TO BE RAISED SHOWING GIN POLE IN FRONT

[MITCHELL]

Erecting Towers

[MITCHELL]

Lowering Tower on to Stubs



[MITCHELL]

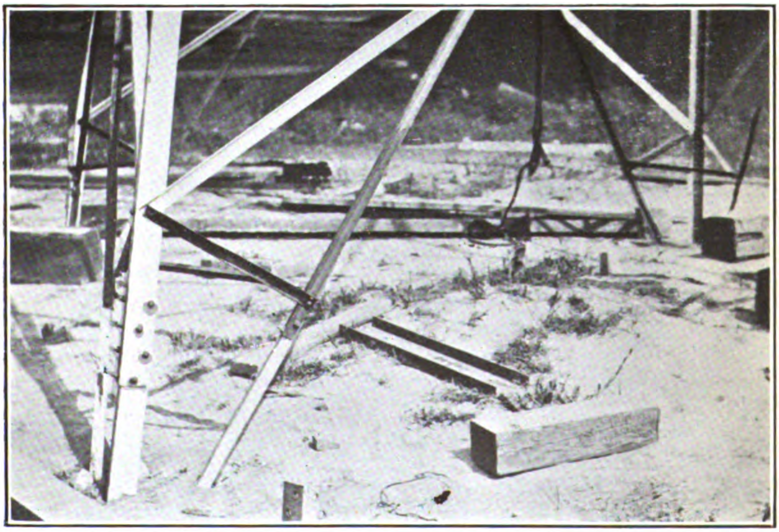
"A" TOWER AFTER APPLICATION OF TEST LOAD OF 12,000 LB.

Eight ½-in. bolts sheared in leg as shown by arrow.

[MITCHELL]

LEG OF TOWER AFTER APPLICATION OF TEST LOAD OF 12,000 LB.

Showing crack in earth and condition of soil in which tower was set.



[MITCHELL]

VIEW OF "A 1" TOWER AT GROUND LINE

by the arrow in one of the illustrations, sheared; the legs of the tower as evidenced by the ground at the base had not moved. These changes produced a tower which we believe has no superior for the same weight.

In traversing such rough country, it was frequently necessary to locate the towers, or one or more legs at least, on a bed of rock. In some cases, the rock was decayed enough to make the use of a grillage footing advisable; in many cases however the foundation was of such stable character that it was practically necessary to use some type of rock anchor. This feature was studied and as a result, the anchor shown in Fig. 3 was developed. It is an angle the same size as the leg angle of the tower which at the lower end has been rounded and scarfed. A hole 2.25 inches in diameter was drilled and the anchor grouted into place. This formed a footing which was materially cheaper and easier to

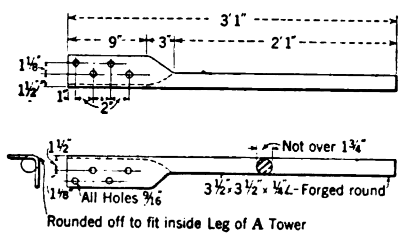


FIG. 3—ROCK FOOTING FOR "A" TOWERS

install than the use of a special tower footing with the two or more anchor bolts.

In excavating, hand drills, coal augers, and a portable gasoline-driven air compressor with a jack hammer drill were used. Forty per cent dynamite was used and practically all holes were shot. The coal augers did not prove satisfactory. The compressor outfit however effected a saving of about 25 per cent over hand drilling. The drawback to it was that it could not be used in very rough country due to the impossibility of getting it near the tower location.

Towers were located by the field engineer from the spotting made in the office on a profile of the line. Reference hubs were set and depth of excavation for each footing marked. All four footings were set at one time using a template, and were leveled up with a carpenter's level and level board, or with an engineer's Y level. The backfill was carefully tamped by hand. Experiments

with a regular gasoline-driven ditch tamper showed very good results where it could be used, but the roughness of the country prevented its use to any large extent.

Examination of footings after one year show only very slight settlement and no movement of tower base whatever. Towers were assembled complete on the ground, the insulators hung on

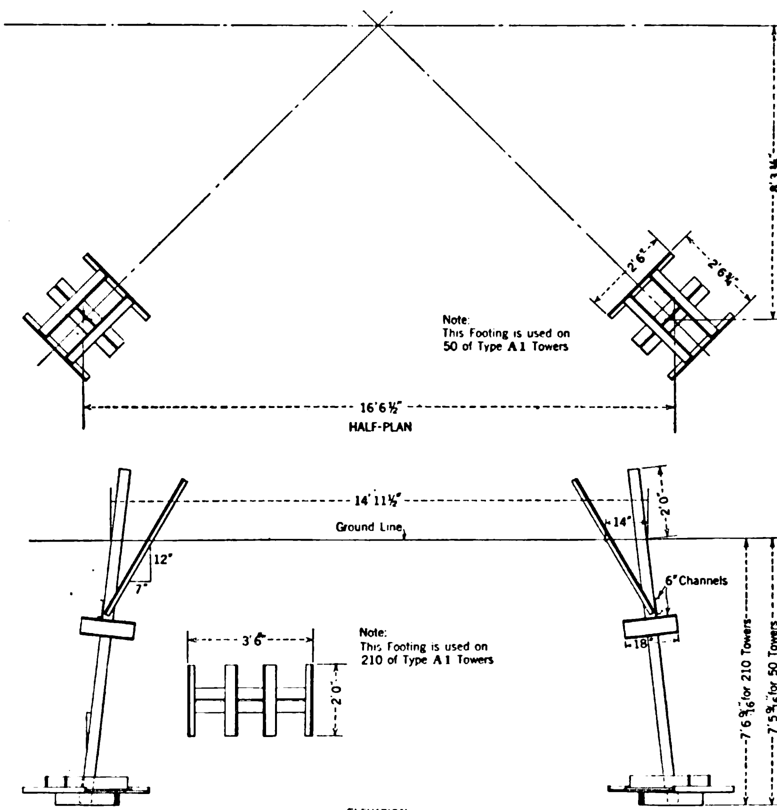


FIG. 4—FOOTING USED ON 50 TYPE "A1" TOWERS

the crossarms, and then raised with a gin pole. The average assembling crew assembled from twelve to sixteen towers per day and the erecting gang raised about the same number. The best record was twenty towers raised in one ten-hour day.

Excavation, setting footings and back fill, with all steel foundations, cost on an average of $28.00 per tower; assembling 4800-pound towers cost $10.00 and erection $5.00.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

IV—A Few Essentials in Town Line Construction

BY P. M. DOWNING

ABSTRACT OF PAPER

In this paper the author briefly emphasizes the fact that the weakest link of any transmission system is the line, and that this part of the plant has never been given the consideration it deserves.

Towers are strongly advocated for important trunk lines, and certain conditions to be met in the design of same are given. The use of concrete footings is recommended in preference to those of metal set directly in the ground.

THE USE of wooden poles in connection with high voltage transmission lines, especially important trunk lines, is fast being superseded by steel towers. The wonderful growth of the electrical industry during the past few years has resulted in the construction of larger generating stations, and the transmission lines carrying these heavier loads have become of correspondingly greater importance.

During all of this time, except for a noticeable increase in the sizes of the units used, there has not been any radical change in the equipment of hydroelectric generating stations. The same general types of turbines and impulse wheels as were used fifteen or twenty years ago, during the infancy of the industry, are still being used. Slight modifications in the design of the generators the use of the better material now available, and higher speeds have resulted in larger units and increased efficiencies. Transformers have kept pace with the generators and water wheels, both as regards size and efficiency, but have never been in any respect the limiting feature in high voltage transmission work.

The line is and has always been the weakest link of the entire system, and it is only during the last few years that this part of the work has received the attention it deserves. Wooden pole lines with pin type insulators were for many years used almost exclusively, regardless of the voltage, or the importance

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of the line; in fact, it was not until 1903 that the first commercial tower line in America was constructed by the Guanajuato Power Co., in Mexico. The first line using towers with suspension insulators was the 140-mile 100,000-volt line of the Stanislaus Power Company in California, (now the Sierra and San Francisco Power Co.).

The tower designs first constructed called for each structure to be self-supporting under strains due to the breakage of all conductors on one side of the tower together with maximum ice and wind strains. This resulted in a heavy, durable structure of high first cost, and imposed a very much more severe condition than could be met by pole lines.

Little attention had ever been given to the determination of the strength of wood poles, either by calculation or actual test, and there is no doubt but that such strength requirements in line towers was unreasonable. Subsequent experience has shown that the average tower is too complicated a structure to accurately calculate the stresses in the different members, and it is now generally conceded that the best and only safe way to get reliable information as to the stability of a tower, is to subject it to actual test.

A very safe condition under which to test towers to be used in a country not subject to severe snow and sleet conditions, is to consider a wind pressure of $14\frac{1}{4}$ lb. per sq. ft. on flat surfaces, combined with a temperature range of 125 deg. fahr., or a pressure of 21 lb. per sq. ft. on flat surfaces under ordinary temperatures; also two broken wires in any span of a circuit carrying six wires. These breakages to be in such positions on the tower as will give maximum strain. The height of the tower will depend on the spacing and the required clearance of the conductor above the ground. Considerable difference of opinion exists as to the most economical length of span that can be used. These range from 400 to 1200 ft., depending to a considerable extent on the character of the country, the climatic conditions and the voltage of the line.

Where the line is subject to heavy snow and sleet conditions, the spans must be short, and very often under such conditions it is inadvisable to place the three conductors in a vertical plane. A very much better and safer construction can be had by using single circuit towers with the conductors in a horizontal plane. Under these conditions any unequal distribution of the snow load on the different conductors will not cause them to come in

contact with each other. On 100,000-volt lines carrying two circuits of three wires each, located in vertical planes on the two sides of the tower, a spacing of 800 to 1000 ft. will generally be found to give maximum economy.

Tower foundations depend largely on the character of the soil in which they are located. In heavy ground a metal footing having sufficient resistance against up-lift may be used, but they are not to be recommended. The permissible strains borne by well tamped dry earth do not always obtain under water soaked flood conditions. Where metal footings without concrete have been used, too often they have been found inadequate and resulted in the ultimate failure of the tower. Under no circumstances, except on very short towers, should single post footings be used. Two or three posts give a much more rigid and substantial construction, but materially increase the first cost of the structure; in fact, for the same factor of safety, it is very doubtful whether under any normal conditions the difference in first cost between the metal and concrete footings will be great enough to justify a decision in favor of the metal.

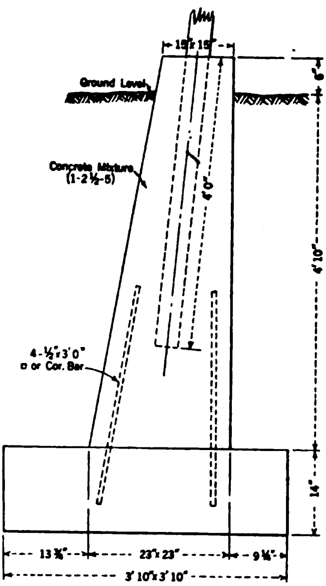

FIG. 1—CONCRETE FOOTING FOR 75-FT. DOUBLE CIRCUIT LINE TOWER

On a number of different lines originally constructed with all metal footings, tower failures have occurred, and it has since been found necessary to reinforce them with concrete.

On the basis of an 800-ft. spacing between towers, and an allowable stress of 15,500 lb. per sq. in. for copper conductors, the sag at 60 deg. fahr. would be approximately, 20 ft. On a double-circuit tower line, having conductors strung to this tension and spaced 10 ft. apart, with a required clearance of 30 ft. above the ground, a 75 to 80 ft. tower would have to be used. The footings of a tower of this height under the assumed load conditions should contain not less than 1¼ cu. yards of concrete per leg, and be of a form similar to that shown in Fig. 1. On the

basis of concrete weighing 140 lb. per cu. ft., earth 110 lb. per cu. ft., and assuming the angle of cleavage of the earth as 30 deg. from the vertical, a footing of this kind would have a factor of safety of approximately two.

In pouring the concrete in a footing of this kind the bottom pan-cake is placed without a form, and allowed to set just long enough to support a metal form for the upper portion.

To insure against weakness due to possible poor bonding along the plane of contact between the upper and lower portions of concrete, it is advisable to use short pieces of reinforcing, or let the metal footing extend well down toward the bottom of the foundation.

The cost of footings of this kind on a line run through average country such as will be found between a hydroelectric plant in the mountains, and a distributing center in the valley, that is. where the route is about equally divided between open mountains and valley, is, approximately, $90.00 per tower, divided as follows:

Labor	$40.00
Material	16.00
Hauling material	34.00
	$90.00

These prices are based on labor at $2.50 to $3.00 per day, and concrete mixed by hand at each tower; average haul for material six to eight miles.

In a country that is not too steep, the most economical way of erecting towers of this size is to assemble them on the ground and end them up into position. One very easy and satisfactory way of doing this is to set a 30 or 35-ft. gin pole just outside of the footings holding it in position by three guys fastened to iron stakes driven into the ground for anchors. Over an open sheave on the top of this gin pole is carried a 0.5-in. flexible steel cable one end of which is connected to the tower at the lower cross-arm, the other to a set of triple blocks made fast to another anchorage 300 or 400 feet from the base of the tower. Where the ground around the footings is not well packed, it is advisable to use hold back anchors on the ground legs, as otherwise the heavy pull against the footings when the tower starts to raise is liable to damage them. A back guy should also be provided to prevent the tower dropping into place as it comes up to a vertical position. Ordinarily side guys are unnecessary, but during windy weather it is well to have them held loosely as the tower raises.

[DOWNING]

FIG. 2—PLACING TOWER FOOTINGS ON A STEEP SIDE HILL BY MEANS OF METAL TEMPLET

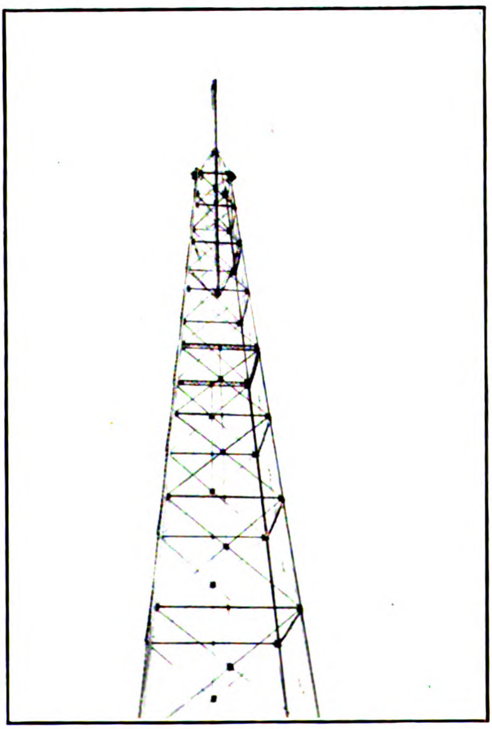

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FIG. 3—A STEEP TOWER BEING ERECTED AT LINE CROSSING OVER A NAVIGABLE STREAM.

Showing a gin pole in the middle of the tower and supported from the four corners of the tower at both bottom and near the top by means of blocks and tackle

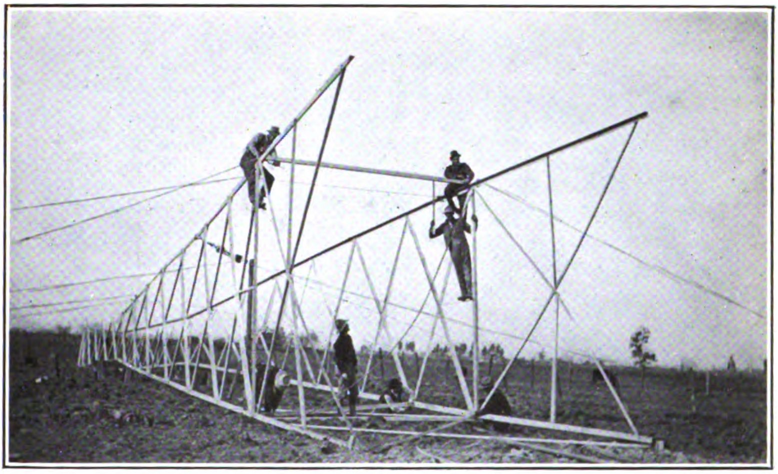

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FIG. 4—A SEVENTY-EIGHT FOOT DOUBLE CIRCUIT STANDARD LINE TOWER BEING ASSEMBLED ON THE GROUND

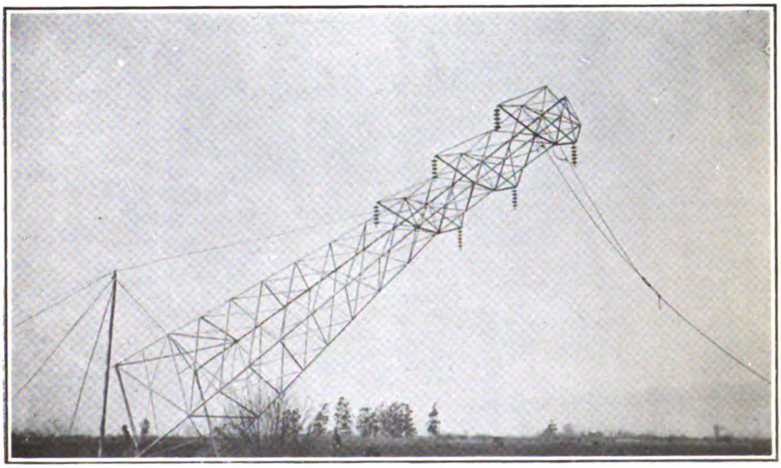

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FIG. 5—A TOWER BEING RAISED INTO POSITION BY MEANS OF A GIN POLE

The best motive power for this work is a 3 ton motor truck which can be used not only for raising the towers, but also for transporting tools and equipment between towers. A crew of nine men with a truck will raise and fasten to the footings an average of 9 towers per work day of 8 to 9 hours. The insulators are attached to the tower while it is on the ground and raised with it.

While there are few, if any, tower lines that have been in service long enough to determine the relative merits as between galvanizing and painting of steel structures of this kind, there is every reason to think that hot dip galvanizing when properly done will prove the more satisfactory in the end. The first cost of painted towers is less than galvanized, but at the very best, the painting will last only a few years. As an offset to the lower first cost of painting, there would be the increased maintenance cost. Moreover the tops of the tower could not be painted with voltage on the line. To do this part of the work, service would have to be interrupted. This objection alone would in many instances be a most serious one, and doubtless, would oftentimes be the determining factor in deciding in favor of the galvanized structures.

There is nothing, thus far, to indicate that there is any appreciable deterioration of the galvanizing when set either in the concrete or directly in the ground. Galvanized tower bolts are not entirely satisfactory. It has been found that almost invariably the bottom of the threads will be so filled up with the galvanizing that the nuts cannot be run on. Sherardizing overcomes this trouble, but is open to the objection that this process is inferior to hot dip galvanizing, and it is often only a matter of a short time when the sherardizing will disappear and the bolts rust. After the tower is erected it should be gone over carefully, all bolts tightened and the threads upset, so that the nuts cannot work loose.

Unless this is done the vibration of the tower due to the wind will, within a few months or a year, cause the nuts to loosen and back off a turn or two, thus materially reducing the rigidity of the tower. This same thing will happen on the clamp bolts holding the conductor, unless lock washers, or some other means, are provided to prevent it.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., July 2, 1915.

THE CALIBRATION OF CURRENT TRANSFORMERS BY MEANS OF MUTUAL INDUCTANCE

THE MEASUREMENT OF MUTUAL INDUCTANCE AND SELF-INDUCTANCE AND ALTERNATING CURRENT RESISTANCE

BY CHARLES FORTESCUE

ABSTRACT OF PAPER.

Reasons are given for the selection of initial inductances as a means for calibrating current transformers, the most important of which is the wide use to which they may be put besides the calibration of current transformers.

The design and manufacture of the apparatus is described, reasons being given for the choice of the form of the secondary coils of the mutual inductances which is a uniformly wound ring, and of the material used for the core, namely marble. The formula used in calculating the values of mutual inductance is given and its limitations stated. Variations in physical dimensions are given and errors in calculated values discussed.

The method of calibrating the mutual inductances is described which illustrates also one method of using the apparatus for measuring mutual inductance.

The method of measuring rates and phase-displacements by means of the apparatus, and the merits of various instrument-for obtaining a balance are described and discussed.

An artificial method of loading the transformers under test is proposed. Its advantages are pointed out.

The use of the apparatus for measuring mutual inductance, self inductance and alternating current resistance is described.

In conclusion it is stated that the apparatus has been satisfactory, and has given little difficulty in manufacture.

INTRODUCTION

THE ACCURATE calibration of current transformers is a problem of considerable commercial importance, but it is only in recent years that this fact has been realized. As a result, null methods of measurement have come to be adopted on account of their convenience and accuracy. The apparatus herein described is believed to be the first commercial application of mutual inductances for measurement of ratio and phase displacement on current transformers.

The use of mutual inductances for measuring the ratio and phase displacement of current transformers is not new; their employment for this purpose is mentioned by Albert Campbell,

Manuscript of this paper was received May 4, 1915.

B. A., of the National Physical Laboratory, in an article in the *Philosophical Magazine*, Vol. XIX, 1910.

The method of using mutual inductances for calibrating current transformers described in the present paper was arrived at independently by the author, though later it was found that a similar arrangement of mutual inductances had been previously proposed by Messrs. Sharpe and Crawford, in a paper presented at the Annual Convention of this Institute on July 1st, 1910, under the subject " Some Recent Developments in Exact Alternating-current Measurements."

The reasons that led me to prefer the use of mutual inductances to that of non-inductive resistances were:

(a) The possibility of calculating the mutual inductance from the physical dimensions and thereby having absolute values.

(b) The ease with which a high degree of sensitiveness may be obtained.

(c) The great flexibility of the method.

(d) The numerous uses to which mutual inductances of the range and character necessary could be put.

In the above mentioned paper, Messrs. Sharpe and Crawford commenting on the use of mutual inductances, say:

" The advantages of this method over the method using resistances are,

(a) The energy expended in the apparatus may be made exceedingly small.

(b) By properly proportioning the numbers of primary and secondary turns on the mutual inductances it is possible to obtain electromotive forces in the galvanometer circuit which are much greater than the drops in the primary coils, hence greater sensitiveness can be obtained without the introduction of an undue impedance in the secondary of the transformer under test.

(c) It is not necessary to connect the primary and secondary circuits together, and leakage effects are therefore reduced.

The disadvantages of the proposed method are

(a) Mutual inductances are not so easily calibrated as resistances.

(b) It is difficult to construct accurate mutual inductances for large currents, although probably not more so than in the case of resistances.

(c) Stray fields effects will influence the ratio directly, requiring astatic construction of the mutual inductances and great pains with the location of the leads carrying heavy currents. '

Messrs. Sharpe and Crawford, however, made no suggestions as to the means to be employed to overcome the disadvantages mentioned. It is hoped, therefore, that the following statement of the means used to overcome these difficulties in a testing outfit which has been in constant use for several years will be of interest not only to those directly concerned with the design, calibration and use of current transformers, but also to the physicist, as exemplifying how methods generally considered as pertaining only to physical laboratories may be adapted for use on commercial testing floors without any particular consideration being given to favorably locating the apparatus.

Design and Construction of the Mutual Inductances

The fact that the apparatus was to be used on a commercial testing floor made it doubly necessary to insure that no external current could affect its accuracy; it was therefore necessary to have mutual inductances as nearly as possible perfectly astatic. It is well-known that a uniformly wound ring of uniform cross-section has no external magnetic force; it follows therefore that its mutual inductance with any circuit which does not encircle it must be zero. On the other hand for a loop encircling the solenoid, the mutual inductance is constant and independent of the size and position of the loop, provided that the secondary winding is very fine and closely wound. This form of coil is therefore admirably adapted for the secondary of a mutual inductance in which variations in value may be obtained by changing the number of primary turns encircling the secondary coil.

Considering the disadvantages enumerated in the paper by Sharpe and Crawford, (b) and (c) immediately disappear if this form of construction be used with fine enough wire in the secondary; for, on account of the astatic features of the ring shaped solenoid, the induced e.m.f. will depend only on the product of the primary current and the number of convolutions of the primary winding and not on the space distribution of the encircling currents. It is therefore as easy with this form of coil to construct accurate mutual inductances for large currents as for small. If the mechanical accuracy of the coil is sufficient to give nearly perfect astaticism, then it should be possible to calculate the mutual inductance accurately enough to make calibration unnecessary. It is, however, not a difficult matter to accurately measure the ratio of two mutual inductances and this is all that

is necessary for the calibration of current transformers, provided that the mutual inductances are known with a fair degree of accuracy. The disadvantage marked (a), is therefore disposed of satisfactorily by this form of mutual inductance.

The circle was chosen for the form of cross-section of the solenoid rather than the rectangle, for the reason that while the latter would have made an easier form to machine the secondary would have been much more difficult to wind in such a manner as to insure perfect adherence of all the loops to the flat sides of the rectangle. A ring of circular cross-section is considerably more difficult to machine accurately, but the secondary coil can be wound on it with greater ease and accuracy.

It was necessary to decide on some suitable material from

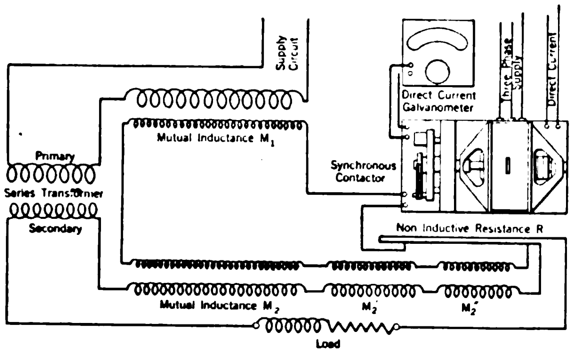

FIG. 1—DIAGRAM OF MUTUAL INDUCTANCE METHOD OF CALIBRATING CURRENT TTANSFORMERS

which to make the rings. On the basis of tests made by the Bureau of Standards, marble appeared to be the most suitable material; it was therefore decided to have rings made of this material and carefully machined to required dimensions. The roughing was done with steel tools, but the finishing cuts were made with a diamond. The variations in external diameters and diameters of cross-section measured at different points were less than 0.001 in. in the finished rings.

Two principal mutual inductances M_1 and M_2 are required for the method of test under discussion, a simple diagram of which is shown in Fig. 1. The other two mutual inductances, M_2' and M_2'', give the fine graduations and do not require to be so accurate. M_2 was designed to give a secondary e.m.f. of approximately four volts with a current of five amperes at a frequency of

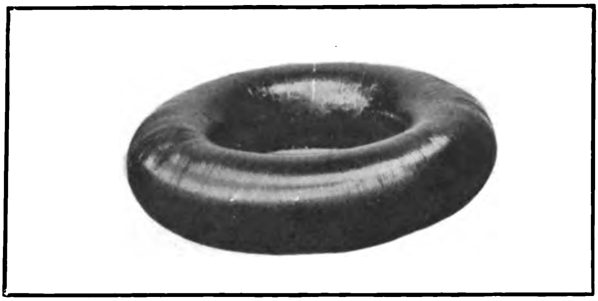

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FIG. 2—COMPLETED SECONDARY WINDING

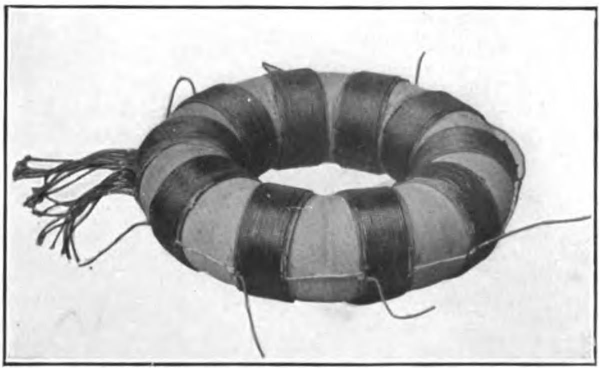

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FIG. 3—M_2 COMPLETE WITH PRIMARY WINDING FIRST USED

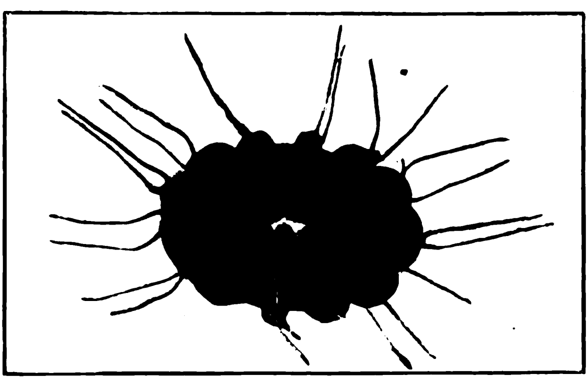

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FIG. 4—M_1 COMPLETE SHOWING 225.5 AMPERE WINDING

tained 414 turns. The dimensions of this ring obtained in the same manner as for M_2 were

Mean radius....................4.02 inches
Radius of cross-section...........1.338 "

The primary winding of M_2 was initially made up of 10 equally spaced coils of 20 turns each, one of which had loops at the end of each turn, but later on this was changed to a winding of 10 closed solenoids encircling the ring of 20 turns each with start and finish leads symmetrically spaced around the perimeter of the ring. This change was made after finding that slight regularities in the winding of the secondary produced differences in the mutual inductance with different coils of the order of 0.2 or 0.3 per cent, and also because it was desired to reduce the self-induction of the primary winding when only a small portion of it was in use.

The primary winding of M_1 for the range of from 5000 amperes to 225 amperes was later added and consisted of 12 single-turn loops symmetrically disposed and arranged for symmetrical grouping.

The values of mutual inductances were calculated by the formula

$$M = 4\pi\, n_1\, n_2\, (a - \sqrt{a^2 - c^2} + 2k\, \sqrt{a^2 - c^2})$$

where a is the mean radius, c is the distance between the center of cross section of the ring and the center of the wire, and k is a function of a, b and c, where b is the radius of the conductor. The value of k is

$$k = \frac{1}{2\cdot 4}\cdot\frac{1}{!2}\left(\delta + \frac{\gamma}{4}\right) + \frac{1.3}{2\cdot 4\cdot 6}\,\frac{1}{!4}\left(3\,\delta^2 + \frac{9}{2}\,\gamma^2\,\delta + \frac{15}{16}\,\gamma^4\right)$$

$$+ \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 8}\,\frac{1}{!6}\left(45\,\delta^3 + \frac{675}{4}\,\gamma^2\,\delta^2 + \frac{1575}{16}\,\gamma^4\,\delta + \frac{946}{64}\,\gamma^6\right) + \ldots.$$

where $$\gamma = \frac{2bc}{a^2 - c^2}$$

$$\delta = \frac{b^2}{a^2 - c^2}$$

The above series for k is rapidly convergent for rings of the proportions given above and the correction is usually extremely small and may generally be ignored. The formula was deduced on the assumption that the current would be uniformly distributed over the section of the secondary conductor. This assumption of course is not absolutely correct and there will be a slight variation in the mutual inductance, both with frequency and also with changes in the radial distance of the primary coil from the secondary winding, due to changes in the distribution of current over the surface of the secondary conductor. Within the range of commercial frequencies the error due to frequency in these mutual inductances was so small as not to be discernible, and that due to differences in radial distance between the primary and secondary windings is probably of the same order of magnitude.

The calculated values of M_1 and M_2 with the maximum number of primary convolutions are

$$M_1 = 0.8265 \text{ millihenrys.}$$
$$M_2 = 3.0222 \quad \text{"} \quad .$$

The value of M_1 was measured by comparison with a mutual inductance which had recently been calibrated by the Bureau of Standards and found to be 0.8216 millihenrys, and the same value was obtained by comparing with M_2, using the above calculated values for M_2. No reason has been found for this large discrepancy from the calculated value, but it has been attributed to a fault in the winding of the secondary solenoid of which there was some evidence, whereas in the case of M_2 we were confident the secondary winding had been done correctly.

General Assembly and Arrangement of Apparatus

The apparatus was assembled so as to secure the utmost flexibility and compactness. The complete apparatus, including panels, dials, and mutual inductances, can be moved as a unit after being disconnected from the testing table. The secondaries of any of the mutual inductances may be reversed and by means of switches the terminals of the measuring device, which in this apparatus at present consists of a direct current galvanometer and a synchronous contactor, may be shunted across the secondary of M_2 or across the non-inductive resistance R in the secondary circuit of the transformer under test.

Panels for M_1 and M_1' which have a common secondary

winding, (M_1', having a primary range 225 amperes to 5 amperes and M_1 having a primary of range 5000 amperes to 225 amperes,) are arranged so that the 12 coils can be connected all in series or groups of one, two, three, four and six coils in series can be connected in parallel between two busbars. Great care was taken in the case of the 5000-ampere winding to arrange the busbars and connections so as to make the stray field a minimum. A test made with 5000 amperes in the primary of M_1 showed no appreciable effect on the secondary winding of M_2.

The primary winding of M-$_2$ is connected to two dials num-

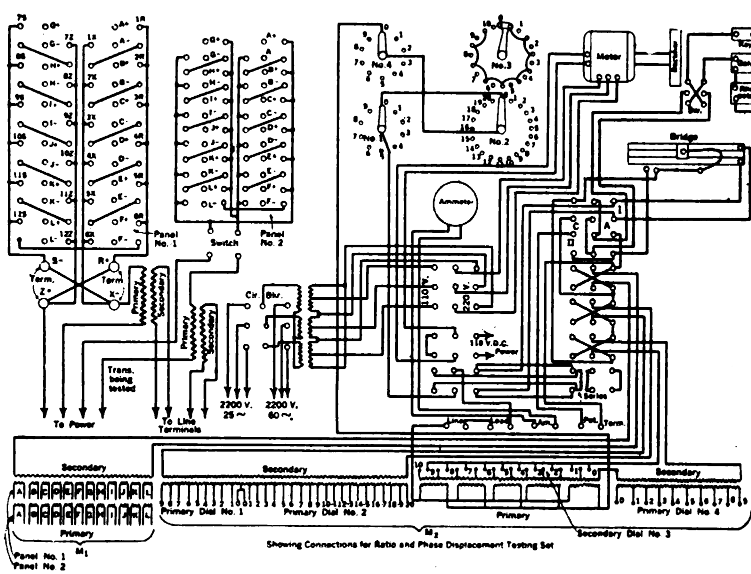

FIG. 5—WIRING DIAGRAM OF APPARATUS

bered 1 and 2, so that it may be cut into the electric circuit by steps of one-half per cent of its total value. M_2' is arranged somewhat differently from this, having a secondary consisting of 10 complete closed solenoids which are arranged to be cut in or out of the secondary circuit of the mutual inductances by steps which are approximately equal in value to 0.0005 of M_2; M_2''- has its primary arranged so as to be cut in and out in 10 equal steps approximately equal to 0.00005 of M_2. The non-inductive resistance R is of manganin and has a sliding contact which carries only the galvanometer current.

In addition to being laid out for measuring ratio and phase

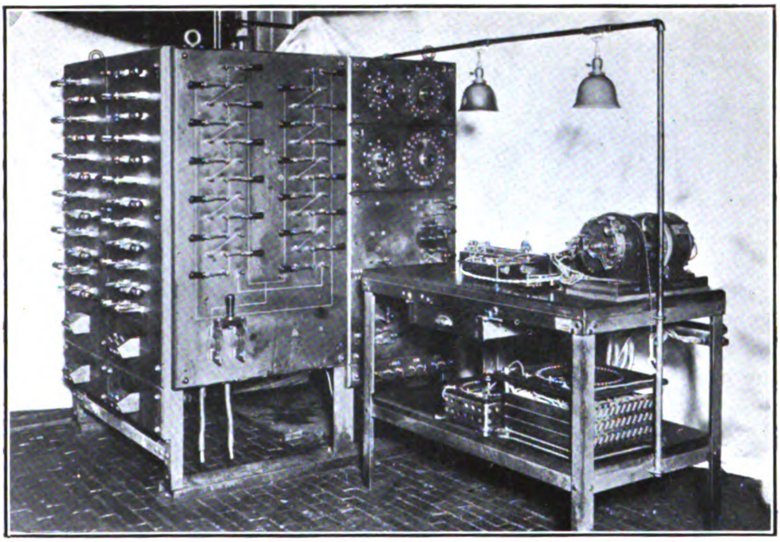

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FIG. 6—GENERAL VIEW OF APPARATUS SHOWING ARRANGEMENT OF PANELS AND DIALS

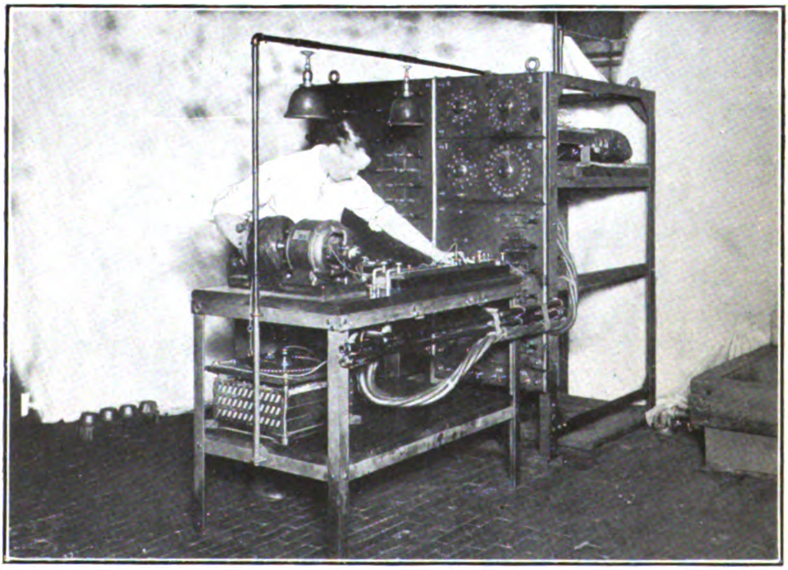

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FIG. 7—GENERAL VIEW OF APPARATUS IN USE

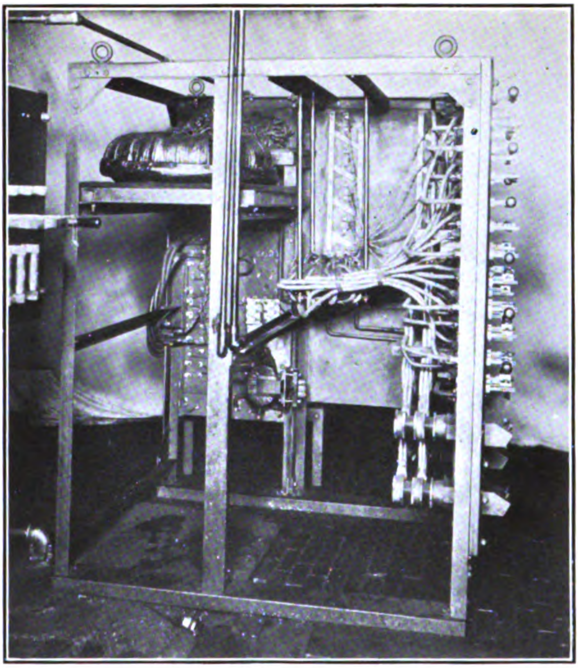

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FIG. 8—BACK VIEW OF APPARATUS SHOWING WIRING OF MUTUAL INDUCTANCES

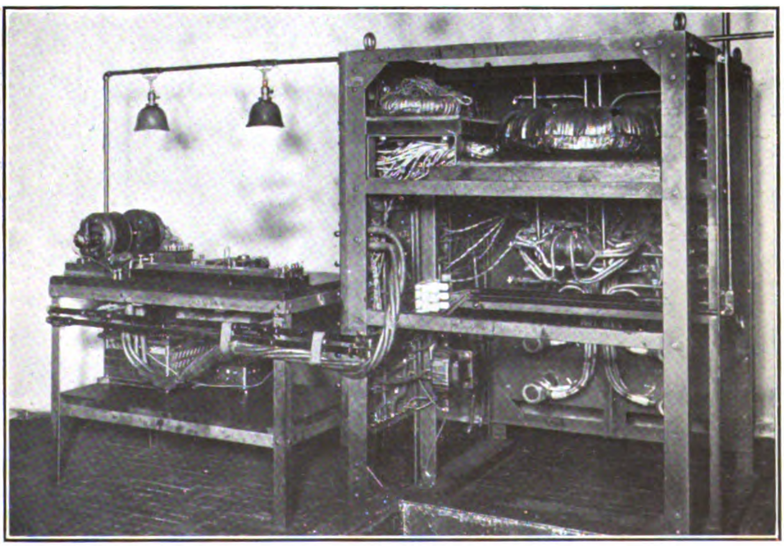

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FIG. 9—SIDE VIEW OF APPARATUS SHOWING ARRANGEMENT AND WIRING OF MUTUAL INDUCTANCE, SYNCHRONOUS CONTACTOR, ETC.

displacement of current transformers the apparatus is arranged for measuring mutual inductance, either by direct measurement or with the aid of an adjustable resistance bridge (Figs. 10 and 13), and for measuring self-inductance and alternating current resistance (Fig. 13). Figures 5, 6, 7, 8 and 9 give a good general idea of the arrangement of the different elements in the apparatus.

Calibration of Mutual Inductances

Owing to the fact that M_1 showed a discrepancy from the calculated value it was considered advisable to measure the ratio M_2/M_1 for all conditions. The method shown in Fig. 10 was used. The rectifier is set at angular positions to give maximum sensitiveness for ohmic and reactive drop respectively.

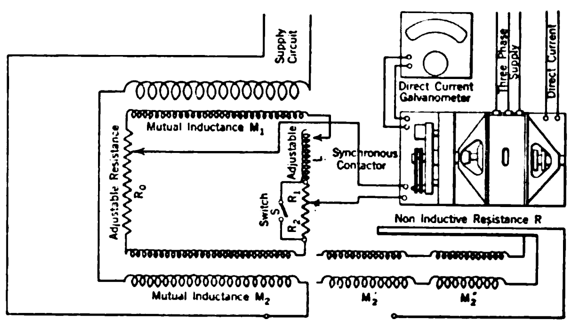

Fig. 10—Diagram of Connections for Calibrating Mutual Inductances

The resistances and reactances of the two sides of the secondary circuit of the mutual inductances are then adjusted by means of the adjustable resistance R_0, and the adjustable mutual inductance L. Switch S is then opened and the resistance arms R_1 and R_2 of the bridge are balanced and if these have mutual inductance a further adjustment ot L will be necessary, in order that the galvanometer shall show zero at all positions of the rectifier. This procedure may be repeated until a satisfactory balance is obtained both with the switch closed and open, then the following relation holds

$$\frac{M_2}{M_1} = \frac{R^2}{R_1}$$

It is not necessary for R_2 and R_1 to be perfectly non-inductive but they must show no change of resistance due to differences in

frequency, that is, their direct current resistance must be the same as their alternating current resistance at commercial frequencies. The resistance bridge used was a five decade bridge, a careful check was made on the accuracy of the bridge by making direct and reciprocal measurements; all measurements checked very closely, the maximum variation from the average of these readings being 0.0002 of the total value. The measurement circuit was arranged so as to avoid as much as possible mutual inductance, but measurements were taken with the secondaries of

TABLE I—MUTUAL INDUCTANCE M_2 IN MILLIHENRIES
DIALS NO 1 and No. 2

Dial No. 2. Points 0 to 20	Dial No. 1. Points 0 to 9									
	0	1	2	3	4	5	6	7	8	9
0	0.0000	0.3024	0.6048	0.9071	1.2095	1.5117	1.8140	2.1161	2.4181	2.7205
1	0.0154	0.3178	0.6202	0.9224	1.2249	1.5271	1.8294	2.1315	2.4335	2.7359
2	0.0305	0.3329	0.6353	0.9376	1.2400	1.5422	1.8445	2.1466	2.4486	2.7510
3	0.0455	0.3479	0.6503	0.9526	1.2550	1.5572	1.8595	2.1616	2.4636	2.7660
4	0.0607	0.3631	0.6655	0.9678	1.2702	1.5724	1.8747	2.1768	2.4788	2.7812
5	0.0759	0.3783	0.6807	0.9830	1.2854	1.5876	1.8899	2.1920	2.4940	2.7964
6	0.0911	0.3935	0.6959	0.9982	1.3006	1.6028	1.9051	2.2072	2.5092	2.8116
7	0.1062	0.4086	0.7110	1.0133	1.3157	1.6179	1.9202	2.2223	2.5243	2.8267
8	0.1213	0.4237	0.7261	1.0284	1.3308	1.6330	1.9353	2.2374	2.5394	2.8418
9	0.1363	0.4387	0.7411	1.0434	1.2458	1.6480	1.9503	2.2524	2.5544	2.8568
10	0.1513	0.4537	0.7561	1.0584	1.3608	1.6630	1.9653	2.2674	2.5694	2.8718
11	0.1666	0.4690	0.7714	1.0737	1.3761	1.6783	1.9806	2.2827	2.5847	2.8871
12	0.1816	0.4840	0.7864	1.0837	1.3911	1.6933	1.9956	2.2977	2.5997	2.9021
13	0.1967	0.4991	0.8015	1.1038	1.4062	1.7084	2.0107	2.3128	2.6148	2.9172
14	0.2117	0.5141	0.8165	1.1188	1.4212	1.7234	2.0257	2.3278	2.6298	2.9322
15	0.2268	0.5292	0.8316	1.1339	1.4363	1.7385	2.0408	2.3429	2.6449	2.9473
16	0.2419	0.5443	0.8467	1.1490	1.4514	1.7536	2.0559	2.3580	2.6600	2.9624
17	0.2568	0.5592	0.8616	1.1639	1.4663	1.7685	2.0708	2.3729	2.6749	2.9773
18	0.2718	0.5742	0.8766	1.1789	1.4813	1.7835	2.0858	2.3879	2.6899	2.9923
19	0.2868	0.5892	0.8916	1.1939	1.4963	1.7985	2.1008	2.4029	2.7049	3.0073
20	0.3017	0.6041	0.9065	1.2088	1.5112	1.8134	2.1157	2.4178	2.7198	3.0222

both mutual inductances reversed with respect to the rest of the circuit and differences were found which amounted to less than 0.0003 of the total value which were found to be due to the self-inductance L, which was not astatic,so the arithmetic mean of the two readings was taken for the true ratio M_2/M_1.

It was found that in the case of M_1, it was only necessary to have the ratios for the series arrangement of the primary coils, the values for the other groupings being equal to that for the series arrangement multiplied by the ratio of the number of

coils in series in the group to the total number. Tests were nevertheless made for the complete range of groupings, both on the 5000-ampere winding, as well as on the 225-ampere winding, the sensitiveness being increased with the larger ratios by using larger primary currents.

Tabulated values of M_2 derived from these tests are given in table I., and the ratios, M_2/M_1, are given in table II. It will be noted how close these values are to the calculated values for a perfectly astatic mutual inductance.

TABLE II—RATIO, $M_2 \div M_1$. FOR SMALL PANEL AND DIALS NO. 1 AND NO. 2.

Dial No. 2. Points 0 to 20	Dial No. 1. Points 0 to 9.									
	0	1	2	3	4	5	6	7	8	9
0	0.0000	0.3680	0.7361	1.1039	1.4721	1.8396	2.2078	2.5752	2.9431	3.3108
1	0.0188	0.3868	0.7549	1.1227	1.4909	1.8584	2.2266	2.5940	2.9619	3.3296
2	0.0371	0.4051	0.7732	1.1410	1.5092	1.8767	2.2449	2.6123	2.9802	3.3479
3	0.0554	0.4234	0.7915	1.1593	1.5275	1.8950	2.2632	2.6306	2.9985	3.3662
4	0.0739	0.4419	0.8100	1.1778	1.5460	1.9135	2.2817	2.6491	3.0170	3.3847
5	0.0924	0.4504	0.8285	1.1963	1.5645	1.9320	2.3002	2.6676	3.0355	3.4032
6	0.1109	0.4789	0.8470	1.2148	1.5830	1.9505	2.3187	2.6861	3.0540	3.4217
7	0.1293	0.4973	0.8654	1.2332	1.6014	1.9689	2.3371	2.7045	3.0724	3.4401
8	0.1476	0.5156	0.8837	1.2515	1.6197	1.9872	2.3554	2.7228	3.0907	3.4584
9	0.1659	0.5339	0.9020	1.2698	1.6380	2.0055	2.3737	2.7411	3.1090	3.4767
10	0.1842	0.5522	0.9203	1.2881	1.6563	2.0238	2.3920	2.7594	3.1273	3.4950
11	0.2028	0.5708	0.9389	1.3067	1.6749	2.0424	2.4106	2.7780	3.1459	3.5136
12	0.2210	0.5890	0.9571	1.3249	1.6931	2.0606	2.4288	2.7962	3.1641	3.5318
13	0.2394	0.6074	0.9755	1.3433	1.7115	2.0790	2.4472	2.8146	3.1825	3.5502
14	0.2577	0.6257	C.9938	1.3616	1.7298	2.0973	2.4655	2.8329	3.2008	3.5685
15	0.2760	0.6440	1.0121	1.3799	1.7481	2.1156	2.4838	2.8512	3.2191	3.5868
16	0.2944	0.6624	1.0305	1.3983	1.7665	2.1340	2.5022	2.8696	3.2375	3.6052
17	0.3126	0.6806	1.0487	1.4165	1.7847	2.1522	2.5204	2.8878	3.2567	3.6234
18	0.3308	0.6988	1.0669	1.4347	1.8029	2.1704	2.5386	2.9060	3.2739	3.6416
19	0.3491	0.7171	1.0852	1.4530	1.8212	2.1887	2.5569	2.9243	3.2922	3.6599
20	0.3672	0.7352	1.1033	1.4713	1.8393	2.2071	2.5750	2.9424	3.3103	3.6780

Use of the Apparatus for Measuring Ratio and Phase Displacement of Current Transformers

Table III shows the approximate panel arrangement and dial setting for transformers of standard ratio. The apparatus is set according to the value shown for the transformer under test and the load is adjusted from a table of resistance and reactance of the apparatus with the help of additional adjustable resistance and reactance which is provided for loading purposes. The angular position of the rectifier contacts which renders the galvanometer most sensitive to reactance e.m.f. is obtained by adjusting

until the galvanometer reads zero with its leads shunted across the non-inductive resistance R_1; in like manner the position for maximum sensibility for ohmic drop is obtained, by a similar adjustment when the leads are shunted across the secondary of M_2. The value of M_2 and R are then adjusted until the galvanometer reads zero, with both the above angular settings of the

TABLE III—APPROXIMATE PANEL AND DIAL SETTINGS FOR GIVEN RATIOS OF TRANSFORMATION.

Ratio of transformation	Coils in multiple	Dial setting for 100% ratio in order of number	Reactance of circuit at 25 ~	Reactance of circuit at 60 ~
5 to 5	1	2-14-3-5	0.01	0.033
10 " 5	1	5-8-7-1	0.04	0.094
15 " 5	1	8-3-0-8	0.088	0.210
20 " 5	2	5-8-7-1	0.04	0.095
25 " 5	2	6-15-9-0	0.062	0.150
30 " 5	2	8-3-0-8	0.087	0.210
40 " 5	3	7-4-9-7	0.07	0.170
50 " 5	3	9-1-2-0	0.108	0.262
60 " 5	4	8-3-0-8	0.088	0.212
75 " 5	6	6-15-9-0	0.062	0.150
80 " 5	6	7-4-9-7	0.07	0.170
100 " 5	6	9-1-2-0	0.108	0.262
120 " 5	12	5-8-7-1	0.04	0.095
160 " 5	12	7-4-9-7	0.07	0.170
200 " 5	12	9-1-2-0	0.108	0.262
250 " 5	1	6-3-6-2	0.05	0.122
300 " 5	1	7-8-3-4	0.073	0.178
400 " 5	1	9-17-8-4	0.13	0.312
500 " 5	2	6-3-6-2	0.05	0.122
600 " 5	2	7-8-3-4	0.073	0.178
800 " 5	2	9-17-8-4	0.13	0.312
1000 " 5	3	8-4-8-6	0.09	0.218
1200 " 5	3	9-17-8-4	0.13	0.312
1600 " 5	4	9-17-8-4	0.13	0.312
2000 " 5	6	8-4-8-6	0.09	0.218
2400 " 5	6	9-17-8-4	0.13	0.312
3000 " 5	12	6-3-6-2	0.05	0.122
4000 " 5	12	8-4-8-6	0.09	0.218

synchronous contactor with apparatus and transformer arranged as shown in (Fig. 1). Under these circumstances according to the elementary theory of this arrangement we shall have

$$\frac{I_2}{I_1} = \frac{M_1}{M_2} \sec \theta$$

Where, θ is the phase angle and is given by

$$\tan \theta = \frac{R}{2\pi + M_2}$$

The above theory assumes transformation to take place without distortion, which is very nearly true in current transformers under light load, but when the load is heavy there may be appreciable distortion. Assuming

$$i_2 = a_1 \cos pt$$

and

$$i_1 = A_1 \cos pt + A_3 \cos 3pt + A_5 \cos 5\,pt + \ldots\ldots\ldots$$
$$+ B_1 \cos pt + B_3 \cos 3\,pt + B_5 \cos 5\,pt$$

The conditions fulfilled by the balance are

$$A_1 + A_3 + A_5 = \frac{M_2}{M_1} a_1$$

$$B_1 + B_3 + B_5 = \frac{R}{pM_1} a_1$$

or

$$\frac{\sqrt{A_1^2 + A_3^2 + A_5^2 + B_1^2 + B_3^2 + B_5^2 + 2(A_1A_3 + A_1A_5 + A_3A_5) + 2(B_1B_3 + B_1B_5 + B_3B_5)}}{a_1} = \frac{M_2}{M_1}\sqrt{1 + \frac{R^2}{P^2 M_2^2}}$$
$$= \frac{M_2}{M_1} \sec \theta$$

It is evident from the above that where there is considerable distortion the ratio as given by the apparatus will not be the true ratio of the root-mean-square values.

The reason that the synchronous contactor or rectifier and the direct-current galvanometer where chosen for this work was on account of the ability to withstand abuse and at the same time the sensitiveness of the galvanometer and its freedom from vibration and from the influence of alternating stray fields. The rectifier has been the principal source of trouble in this outfit, due to the breakage of springs and contacts. This trouble, however, occurs only at the highest frequencies, namely 50 to 60 cycles, and no trouble is experienced when operating at 25 cycles.

If it were not influenced by stray fields and vibration, I believe a sensitive dynamometer, having one coil excited from a syn-

chronously driven sine-wave generator provided with means for changing the phase angle of the armature, would be preferable to the rectifier and direct-current galvanometer for use with this outfit. If it were possible to produce a pivoted instrument of this type sufficiently sensitive for this work a further advantage would be obtained.

The vibration galvanometer has been recommended for this class of work, but though I have had no actual experience with it, it does not appeal to me very strongly on account of the difficulty of using it and its sharp frequency resonance. There is no way of rendering it sensitive to a change of M only, or to a change of R only. However, the latter difficulty might be overcome by viewing it through a synchronous stroboscope, which is provided with angular adjustment.

The Einthoven string galvanometer used in a similar manner has been suggested and is about to be tried with this apparatus. It has a much flatter resonance curve and can be used with almost equal sensibility within a five per cent range of frequency. The nodal vibrations of the string have given some trouble when the instrument has been used in certain kinds of null method testing and it is feared that similar troubles may be experienced when used with this apparatus.

All the last mentioned schemes of balancing ignore the distorting harmonics or give the ratio of fundamental primary and secondary components, and their phase displacement. This is the measurement required where the current transformer is to be used on a sine wave circuit in connection with the wattmeter.

Proposed Artificial Method of Loading Transformers Under Test

It is often desirable to obtain calibration curves on current transformers at extremely low loads and often at no-load or short circuit. The primaries of M_2, M_2' and M_2'', were designed so as to have very low values of resistance and reactance; the actual resistance of the secondary circuit including the 0.01 ohm non-inductive resistance and all the primaries of M_2, M_2', and M_2'' in series, is slightly less than 0.1 ohm., and the reactance is 0.32 ohm at 60 cycles, and 0.13 ohm at 25 cycles. It is possible therefore even with the dial settings which give maximum sensibility to obtain calibrations with this apparatus at very low loads, but there is a decided drawback due to the fact that the power factor of the load cannot be made exactly unity or

exactly zero. To obviate this difficulty I propose to use two similar transformers in series, the apparatus being arranged so that the total primary current of one transformer alone passes through the primary of M_1; across the primary of this transformer and of M_1 inductances or resistances are shunted as shown in Fig. 11 until the desired load is obtained on the transformer under test. If the phase angle of the load on this transformer only is to be shifted, then reactance may be shunted across both the primary of this transformer and of M_1 in series, and resistance may be shunted across the primary of the other transformer or vice versa; according as it is desired to produce a leading or a lagging power factor. There are a number of ways of varying this method of loading transformer under test, some of which are being tried out with this apparatus. For measuring the value

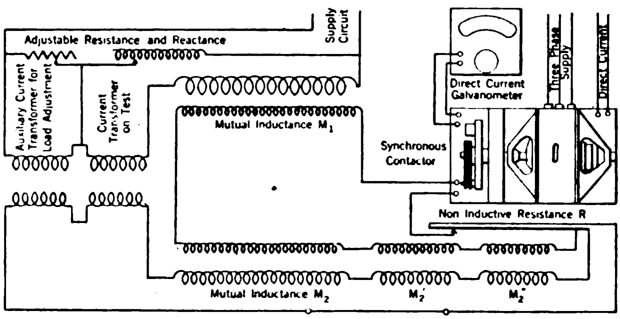

FIG. 11—DIAGRAM OF CONNECTIONS FOR ARTIFICIALLY LOADING A CURRENT TRANSFORMER ON TEST

of the artificial load taken by the secondary of the transformer under test, a modification of the scheme described in the next paragraph (Fig. 13) will be used.

METHOD OF MEASURING MUTUAL INDUCTANCE, SELF INDUCTANCE AND ALTERNATING CURRENT RESISTANCE

For the measurement of mutual inductance, the secondary of M_1 is cut out of the galvanometer circuit by opening a switch and placing a jumper across its jaws. The power lines are connected to the terminals to which the secondaries of current transformers for calibration are connected, and the primary of the mutual inductance to be measured is connected across the terminals marked "load." A diagram of this arrangement for testing mutual inductanc es is shown in Fig. 12. The synchronous

contactor and galvanometer are set to give maximum sensibility for reactance and are connected so as to indicate the difference between M_2 and the mutual inductance to be measured, M_2 is then adjusted until the galvanometer reads zero. If the mutual inductance is larger than M_2, an additional standard mutual inductance may be connected in series with M_2.

To measure self inductance and alternating current resistance the arrangement shown in Fig. 12 is used. This differs principally from the method of measuring mutual inductances by having the non-inductive resistance R supplied with current from the primary circuit through a unity ratio current transformer in series with the galvanometer circuit so that an e.m.f. in phase with and proportional to the primary current may be intro-

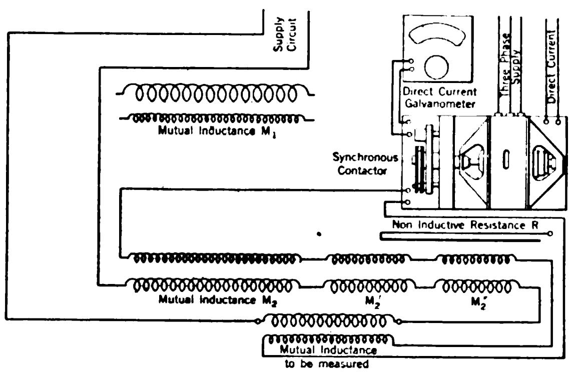

FIG. 12—DIAGRAM OF CONNECTIONS FOR DIRECT MEASUREMENT OF MUTUAL INDUCTANCE

duced. The self-inductance to be measured is placed across the terminals marked "load," and potential leads are carried from the terminals of the self-inductance to the terminals on the apparatus marked "potential," and a balance is obtained by adjusting M_2 and R, with the rectifier in the angular positions to give maximum sensibility for each of these conditions until zero readings are obtained in each case. The readings of M_2, and M_2' and M_2'', give the self-inductance and the value of R the resistance. This method is in general use for measuring the alternating current resistance of current-limiting reactance and some very interesting observations have been made with its help. The method is so sensitive that the effect of the proximity to a large reactor of a man with keys in his pocket can be detected. It was found that when

measuring large reactors the presence of any other reactors in the neighborhood, having multiple wound coils, had a large effect on the apparent alternating-current resistance, due to the circulating currents set up in them through mutual inductance.

Conclusion

The apparatus has proved to be very satisfactory. Little trouble was experienced with the design and manufacture of the mutual inductances. It is believed that the design, manufacture, and calibration of reliable non-inductive resistances for the same range of current values for the first time would have been a much more troublesome task.

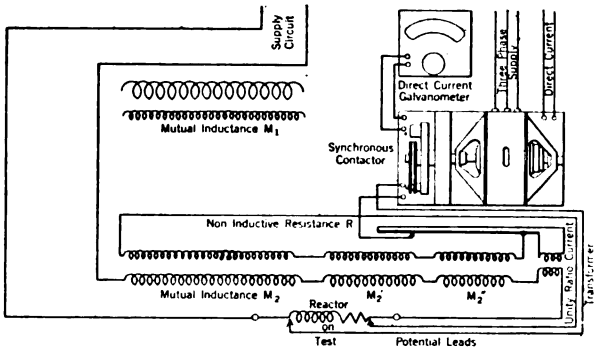

FIG. 13—DIAGRAM OF CONNECTIONS FOR MEASURING INDUCTANCE AND ALTERNATING CURRENT RESISTANCE

A higher degree of sensibility may be obtained with this method than with the shunt resistance method and it is believed to be in many respects more accurate. There is no correction to be made in the phase angle measurements, whereas in the case of shunts corrections may have to be made due to the reactance of the non-inductive resistances. It is believed that the accuracy is well within one part in 10,000 for any setting.

The apparatus has many other possible applications besides those already mentioned and has fully justified its cost.

I wish to take this opportunity to thank Dr. Sharpe for advice given in connection with the design of the synchronous contactor.

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THE INDUCTION WATT-HOUR METER

BY V. L. HOLLISTER

ABSTRACT OF PAPER

The paper discusses the principles and theory of operation of the induction watt-hour meter. The problem of the meter broadly stated is to construct an electric motor the speed of the rotating member of which shall be directly proportional to the electric energy supplied to its windings, such proportionality to be maintained for all conditions of operation. The method of compensation is discussed and also the effect of change in frequency and wave shape. The rotating field principle on which some foreign instruments are based is treated mathematically and the construction of the shifting field meter is also described.

THE OBJECT of this paper is to discuss the theory of operation of the induction watt-hour meter, and to give an exposition of the working principle. No attempt will be made to compare commercial meters. The study has been undertaken for the purpose of a recent research which had for its object an attempt to discover the degree of compensation of the commercial instrument and its approach to the ideal performance. The general problem of the watt-hour meter may be stated as follows; to construct an electric motor such that the speed of the rotating member shall be directly proportional to the electrical energy supplied through its windings, such proportionality to be maintained for all conditions of operation, involving change of wave shape, change of power factor, and throughout the life of the apparatus. The induction meter consists of a light rotating member which moves in front of two systems of alternating magnets. The essential feature is that one system of magnets must, by the rate of change of flux set up, induce within the rotating member current, which current must flow in a path in front of the second system of magnets and through the flux set up therefrom. The principle, therefore, reduces to the action of the direct current motor, *i.e.* a current bearing conductor placed within a magnetic field. The rotating member is usually an aluminum disk or cylinder.

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One system of alternating magnets is excited by being connected across or between the wires of a circuit and hence receives a current depending directly upon the potential impressed and inversely upon the impedance of the windings of these magnets. The other system of alternating magnets is wound to a very low impedance and placed. in series with the circuit to which it is connected, such that the current through the windings depends upon the current drawn in such circuit.

It is true that the principle of the shaded-pole motor has been applied to this class of instruments but with one exception such instruments have not proved satisfactory. The creeping-field shaded-pole meter is an extension of the latter principle, highly

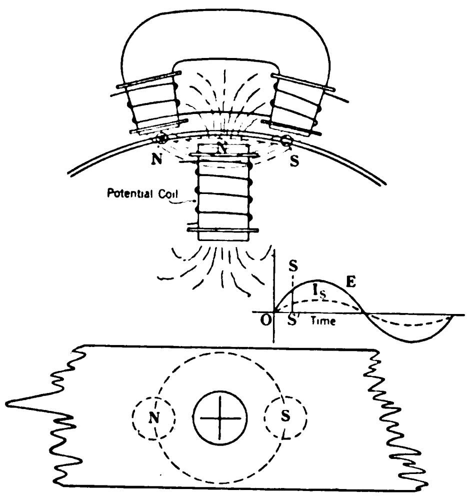

FIG. 1—INDUCTION WATTMETER

interesting but not in commercial use in this country so far as the writer is aware. There were several induction type ampere-hour meters placed upon the market during the early days of the electrical development but as they are not used to any great extent the principle will not be considered.

THEORY

The flux set up by the potential magnet coil threads through the disk or rotating member and induces therein eddy currents. The eddy current path and its relation to the generating flux, potential magnet pole, and series or current magnet poles is shown in Fig. 2. by the line *iii*. The eddy currents set up

within the disk by the inducing flux from the series magnets is indicated in relative position and path by the double circles *mmm*, and *m'm'm'*. The eddy currents *mmm*, and *m'm'm'* react with the flux from the potential coil to produce a turning torque; while the current *iii* reacts with the flux from the series coils to produce an additional turning torque. In the discussion following, that reaction only is considered, which is produced by the currents *mmm*, and *m'm'm'* and the flux from the potential coil. It is thought that this latter reaction may be used to explain all of the phenomena involved and undue complications may be eliminated. However, it is true and must be borne in mind that the flux from the potential coil by its rate of change induces an eddy current within the disk which, pursuing its path of circular form in front of the poles of the series magnets gives rise to a torque additive to the above. As these two eddy currents—that due to the series flux and that due to the potential flux—are in time phase quadrature, the torque of the meter is very nearly uniform. From the consideration of the eddy current from the series coil and the flux from the potential coil, alone it would seem that the torque of the meter is a pulsating quantity varying at double frequency. From an analysis of both eddy currents and fluxes involved it is seen that the torque is due to two reactions in time phase quadrature hence, approximately uniform in value.

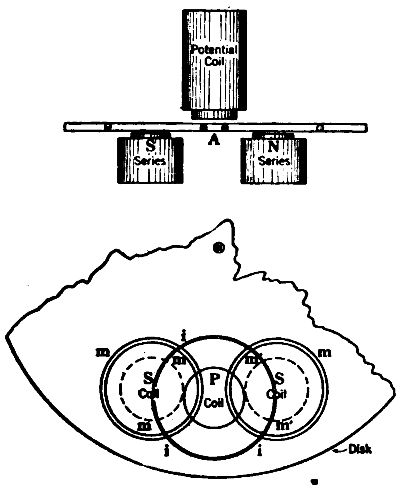

FIG. 2—VIEW FROM ABOVE—SHOWING EDDY CURRENT PATHS

Some authors prefer to look upon induction watt-hour meter as being similar to the polyphase induction motor. They point out that the magnetic field in the region of the point marked A, Fig. 2, is the resultant of two magnetic fields in time phase and space quadrature. It seems preferable in order to simplify the discussion of the general induction meter to disregard this rotating field phenomenon since it may be pointed out that there are meters on the commercial market

the action of which is due entirely to the shifting of a magnetic field and in which two quadrature magnetic fields are not present. Further, it might be pointed out that the direction of rotation of the disk is independent of its position with regard to the center of the rotating magnetic field.

Notes on Revolving Field Principle

The theory that an induction watt hour meter operates due to a revolving magnetic field rests upon the observation that there is in such a meter two magnetic fields set up which, in space, are at right angles and, in time phase relations, in quadrature. It is well known that these are some of the essential relations existing in the revolving magnetic field induction motor. A careful investigation of the construction of any, and I might say, all induction watt-hour meters reveals that such main revolving magnetic fields as are set up have their centers of rotation within the disk and revolve in a plane perpendicular to the moving element. Supposing that the principal driving force acts as if the revolving magnetic field were a traction roller or disk, we can readily see that, provided the moving element of the meter were off center with regard to the driving disk, the meter moving element would be caused to revolve. We can see no reason why the moving element would receive any driving impulse when it is passing through the center of the revolving magnetic field. Mechanically adjusting the moving element of the meter so that it passes either above or below the center of the axis of the revolving magnetic field would cause the meter disk to revolve either to right or left, or to reverse its direction of rotation when its position is changed and to stand still when coincident with the axis. Since from actual experiment with this action in mind that meter does not reverse its direction of rotation, neither does it have zero torque at any position, we become convinced that this is not the principle of operation.

We are next interested in the production of revolving magnetic fields in the plane of the moving element of the disk by the intersection of the components of the main fields. These new revolving magnetic fields are present since one of the component field in its return path through air takes a direction at right angles to its original path at the point of emanation from the inducing pole. These subsidiary revolving fields, there may be a large number of small whirls, are seen to act

upon the moving disk at different radii, also in different directions, and the advocates of this theory, state that the turning torque is the difference between the positive and negative torques operating at different distances from the center of rotation. To investigate this theory we attempt to find out if there still remains positive torque if the radius of the meter disk is made very great—approaching infinity; further, if the meter reverses its direction of movement when the center of rotation of the disk is changed from one side of the axis of the magnetic field to the other. (see Fig. 3.) Experiment fails to substantiate either of these suppositions. In fact, the disk of the meter moves in the same direction through the magnetic field whether the center of rotation is to right or left. Further, the drum type of meter shown in Fig. 4 does not reverse its direction of drum-movement through the field, if the curvature of the moving element is reversed. In Fig. A the direction of the movement is the same for both disks, shown in solid and dotted lines.

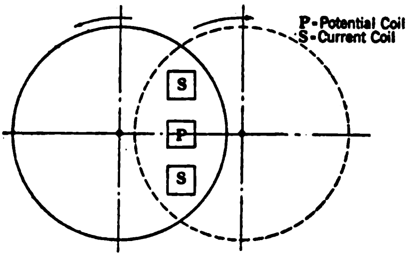

FIG. 3—SHOWING DIRECTION OF ROTATION OF DISK WHEN PIVOTED ON EITHER SIDE OF DRIVING ELEMENTS

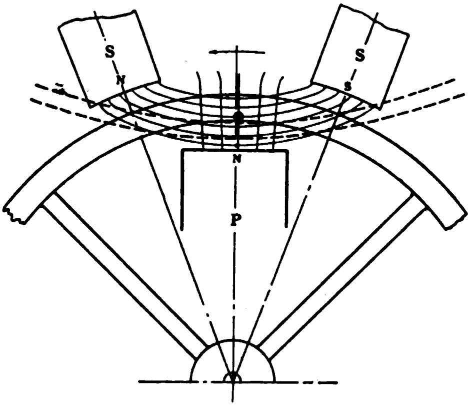

FIG. 4

There is one very desirable element in the evidence to disqualify the " revolving field theory" which to date has not been

obtained. The characteristic of the revolving field induction motor is its approach to a synchronous speed being dependent upon the frequency of the current supplied and poles of the motor. To date we have not been able to build a satisfactory induction meter that would any where attain to a synchronous speed for a two pole motor. If the induction meter should show a definite synchronous speed of rotation, or linear speed of disk movement, corresponding to the synchronous speed of the revolving magnetic field present, we should have evidence upon which to establish the revolving field principle and theory.

It may be remarked in passing, that if the revolving field principle were the true theory, the induction meter which has a drum-shaped revolving element would have a much weaker driving torque than the flat disk type of meter since the thickness of the disk in the former is small and, hence the difference

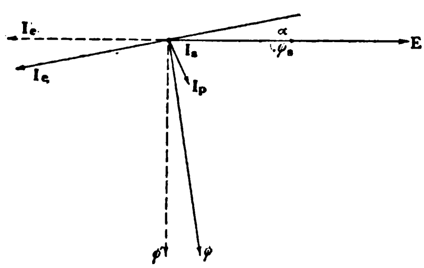

Fig. 5

in radii of the acting whirls of magnetic fields would be very small. Since the meter of the drum type shows no such unfavorable comparison with meters of the disk type, the contention is faulty.

Vector Diagram. Let E in Fig. 5 represent the impressed electromotive force on a circuit to which the induction watt-hour meter is connected. Let I_p represent the current in the potential coil. I_s represents the current in the series coil. ϕ_s is the flux from the current coil. ϕ_p is the flux from the potential coil. I_e is the eddy current *mmm* and *m'm'm'* in the disk and θ is the power factor angle or the angle between I_s and E.

The flux due to the magnetomotive force of the series coil must be in phase with such magnetomotive force and hence ϕ_s is in phase with I_s. The flux ϕ_p must be very nearly 90 deg. behind E in time phase position as the potential circuit

is highly inductive. The angle of lag of the electromotive force induced in the disk by the rate of change of the flux ϕ_p must necessarily be 90 deg. behind the inducing flux, and, since the eddy current path is practically non-inductive, I_e is 90 deg. behind ϕ_p in time phase.

From the considerations effecting torque it is found that the speed of the rotating member of the meter depends upon the product of the eddy current in the disk by the flux from the series coil multiplied by the cosine of the angle between the same vectors. It is, therefore, clear that such torque will be a maximum when the angles alpha and theta are zero; that is, for the perfectly compensated meter and for those conditions of load which give unity power factor. It is similarly evident that in the meter for which alpha is a definite angle, say 15 deg., the driving torque will be a maximum for those conditions of load which make the current leading by 15 deg. Such a meter operating at a greater speed for a given current supply and electromotive force impressed at a leading current of 15 deg. or power factor of 96 per cent, does not maintain its accuracy when the power factor is varied.

It may be readily appreciated from an inspection of the diagram that any change in the condition of operation of the meter which changes the value or the phase position of the vector I_p with regard to E, changes the angle alpha. The object of the compensating coils in general is to reduce this angle. Hence the ideal meter should give a vector diagram similar to Fig. 5 where alpha has been reduced to a minimum,—shown dotted. Similarly, the ideal meter would be one in which little or no power were consumed, or I_p should have a phase angle of 90 deg. behind E.

Torque. The torque of the induction watt-hour meter depends upon the force acting upon a current-bearing conductor placed within and at right angles to a magnetic field.

Let $\phi = \phi_m \sin \omega t$ be the magnetic field set up by the series windings of the meter; and

$i = I_m \sin (\omega t - \beta)$ be the eddy current caused to flow in the disk by the e.m.f. induced in the disk due to the value and rate of change of the flux from the potential coil: Then, by Faraday's law

$$F = IlH$$

T = torque ∞ $i\phi l$. Where l is the active length of the conductor.

All units are chosen in the c.g.s. system. Therefore

instantaneous $F = I_m \sin(\omega - \beta)\ \phi_m \sin(\omega t)\ l$, or
maximum $F_m = I\ \phi_m\ l \cos[I\phi_m]$

Maximum torque will occur during that instant for which $\omega t = 1$

The greatest value of torque will be realized at unity power factor in the meter for those conditions which produce $\alpha = 0$. deg. α is called the natural angle of the meter and, since its value depends in modern meters upon the degree and method of compensation, that meter is perfectly compensated for which $\alpha = 0$. deg.

Frequency. A frequency higher than that for which the meter has been calibrated, for the same value of load current, increased the eddy current due to the flux from the current coils in direct proportion. The e.m.f. set up within the disk is

$e = \dfrac{d\phi s}{dt}$, where ϕs is the flux from the series turns.

Or the eddy current $I_e = \dfrac{e}{r} = \dfrac{d\phi s}{dtr}$, where r is the resistance of the same current path.

The flux from the potential coil, if the latter is highly inductive, varies as $\dfrac{E}{f} = \dfrac{\text{Impressed e.m.f.}}{\text{frequency}}$ Hence, for a constant applied pressure the flux from the pressure coil will vary inversely proportional to the frequency which is precisely the condition for meter accuracy.

Since $T \propto I \sin(\omega t - \beta)\ \phi_m \sin(\omega t)\ l$ is the torque equation for normal frequency, at double frequency we have

$$T, \propto 21 \sin(2\omega t - \beta)\ \frac{\phi_m}{2} \sin(2\omega t)\ l$$

The latter equation shows that the accuracy of the meter is maintained at the higher frequency if the natural angle remains unaltered. In general, since the latter relation does not hold, the meter must not only be compensated for the normal frequency but in all probability must have the compensating device adjusted anew for the higher-frequency operation.

We have assumed in the above that the potential coil is highly inductive, that is, the counter e.m.f. developed due to self

induction is very nearly equal to the impressed e.m.f. If such is not the case, it is probable that the exciting current in the potential winding will not have the same value at all frequencies, due to the change in the permeability, hence the similar change in the value of the coefficient of self inductance L at different flux densities.

The value of the angle α depends upon the inductance of the eddy current circuit, as well as the angle between E and ϕ_m, hence all induction watt-hour meters should have some provision for changing the amount of the compensation for operating the meters on high frequency.

Effect of Temperature. An increase of temperature of the coils and working parts of an induction meter primarily increases the resistance of the conductors. Other effects such as increased friction, or a change in magnetic permeability are of no consequence or are negligible.

An increase of resistance of the series coils cannot appreciably affect the series or load current nor the accuracy of the instrument. An increase of the resistance of the eddy current path reduces the eddy current and hence directly diminishes the driving torque. However, the resisting or braking torque, depending as it does upon the reaction between eddy currents set up within the disk and by reacting with the magnetic field of the permanent magnets, is diminished in proportion. Hence, the net effect upon the accuracy of the meter of the increase in resistance of the eddy current path is nil. The increased resistance of the potential coil due to an increase in temperature reduces the current therein which, in turn, reduces the mangetomotive force and flux through and from such coil. The resultant reduction in torque decreases the accuracy of the meter immediately. To avoid this inaccuracy, there is open to the manufacturer the course of winding the potential coil with a wire having a zero temperature resistivity coefficient. From this standpoint the more highly inductive potential winding is preferable.

Wave Shape. It has been observed that induction meters retain their accuracy on circuits of widely different wave form. That such should be the result is not apparent from a casual study but may be investigated mathematically as follows:

It may be proved mathematically that if we have an e.m.f. wave, complex in form, represented by the following equation

$$e = E_1 \sin \omega t + E_3 \sin 3\,\omega t + E_5 \sin 5\omega t \ldots \text{etc.} \qquad (1)$$

which produces within a circuit a current i—

$$i = I_1 \sin(\omega t + \lambda_1) + I_3 \sin(3\,\omega t + \lambda_3) + I_5 \sin(5\,\omega t + \lambda_5)\ldots\text{etc.} \tag{2}$$

that the power represented is

$$\begin{aligned} ei = {} & E_1 \sin \omega t \cdot I_1 \sin(\omega t + \lambda_1) \\ & + E_3 \sin 3\,\omega t \cdot I_3 \sin(3\,\omega t + \lambda_3). \\ & E_5 \sin 5\omega t \cdot I_5 \sin(5\,\omega t + \lambda_5) \\ & \ldots\ldots\ldots\ldots\text{etc.} \end{aligned} \tag{3}$$

or, the power w at any instant.

$$w = e_1 i_1 + e_3 i_3 + e_5 i_5 \ldots\ldots\text{etc.} \tag{4}$$

Where e_1, e_3 and e_5 are the instantaneous values of the harmonic e.m.fs. indicated by the subscripts; i_1, i_3 and i_5 are the corresponding currents. The demonstration of this conclusion depends upon the fact that the integral of two sine functions of different commensurable periodicities is zero when the limits are taken for a complete period of the fundamental.

If the e.m.f. represented by equation (**1**) is impressed upon the potential circuit of an induction meter, the flux due thereto may be found as follows:

$$E \,\alpha\, \frac{d\phi}{dt}$$

hence $\phi = K \int E\,dt$

or

$$\phi = K \int e\,dt = K \int (E_1 \sin \omega t + E_3 \sin 3\,\omega t + E_5 \sin 5\omega t)dt \tag{5}$$

$$\phi = \frac{K}{\omega}\left[\frac{-E_1 \cos \omega t}{1} - \frac{E_3 \cos 3\,\omega t}{3} - \frac{E_5 \cos 5\,\omega t}{5}\right]. \tag{6}$$

The currents in the series coil will be as given in equation (**2**), and, hence, the flux from the series coil will be represented by some constant multiplied into equation (**2**) for constant reluctance of magnetic current. The instantaneous torque of the meter, being proportional to the power passing through the circuit should be represented by

$$t = K' \,(e_1 i_1 + e_3 i_3 + e_5 i_5 \ldots\ldots\ldots\ldots\text{etc.}) \tag{7}$$

However, the torque has been shown to depend upon the product of the eddy current within the disk and the flux penetrating the disk along the eddy current path.

The eddy current due to the potential coil flux is:

$$i_{e-p} = \frac{i}{R_e} \frac{d\phi_p}{dt}$$

$$i_{e-p} = \frac{1}{R_p} \frac{d}{dt} [K \int E \; edt] = \frac{1}{R_e} \cdot K \cdot e. \tag{8}$$

$$i_{e-p} \frac{1}{R_e} \cdot K \cdot [e_1 + e_3 + e_5 \ldots \text{etc.}]$$

The flux from the series coil will be

$$\phi_s = K''' [i_1 + i_3 + i_5 \ldots\ldots \text{etc.}] \tag{9}$$

Hence, the torque, instantaneous.

$$t \propto i_{e-p} \cdot \phi_s = \frac{1}{R_e} \cdot K \cdot K''' [e_1 i_1 + e_3 i_3 \ldots\ldots \text{etc.}] \tag{10}$$

The torque due to the flux from the series coil and current set up by the potential flux is accurately proportional to the power.

The flux set up by the potential coil ϕ_p is given by equation (6). The eddy current set up by the flux from the series coil is

$$i_{e-s} = \frac{d\phi_s}{dt} \frac{1}{R_e}$$

$$i_{e-s} = \frac{1}{R_e} K^{IV} \frac{d}{dt} [I_1 \sin(\omega t + \lambda_1) + I_3 \sin(3\omega t + \lambda_3) + I_5 \sin(5\omega t + \lambda_5) + \ldots \text{etc.}]$$

If we assume for the sake of simplicity that λ_1, λ_3, λ_5, etc. are each zero, then

$$i_{e-s} = \frac{1}{R_e} K^{IV} \frac{d}{dt} [I_1 \sin \omega t + I_3 \sin 3\omega t + I_5 \sin \omega t + \text{etc.}]$$

and

$$\phi_p = \frac{K}{\omega}\left[-E_1 \cos \omega t - \frac{E_3}{3} \cos 3\,\omega t - \frac{E_5}{5} \cos 5\,\omega t + \text{etc.}\right]$$

and

$$\begin{aligned} T\,\alpha\,\frac{1}{R_e} K^{IV} \frac{K}{\omega} \Big[& -\omega I_1 \cos \omega t \cdot E_1 \cos \omega t \\ & - 3\,\omega I_3 \cos 3\,\omega t \,.\, \frac{E_3}{3} \cos 3\,\omega t \\ & - 5\,\omega I_5 \cos 5\,\omega t \,.\, \frac{E_5}{5}\, 5 \cos \omega t \\ & - \text{etc.} \Big] \end{aligned} \qquad \textbf{(11)}$$

Which reasoning leads us to conclude that the torque is directly proportioned to the power transmitted through the winding of the meter at each instant by currents and electromotive forces of pure sine waves or complex waves.

Equation (**11**) shows that the torque produced by the eddy currents induced within the disk by the series coil fluxes reacting with the potential coil flux is in time quadrature with the torque previously considered. The negative sign is not to be interpreted as applying to the torque, but as simply indicating the time sequence of the two torques, one expressed as a sine function the other a cosine function.

Special Meter Details

Rotating Field Meters. There are some forms of alternating-current instruments of foreign make which afford interesting examples of the application of the principle of the rotating field. With reference to the apparatus and arrangement shown in Fig. 6, which consists of a set of stampings provided with four projecting poles and a copper cylinder carefully pivoted coaxially with them, the arrangement is essentially that of a quarter-phase induction motor. The two poles *AA* are wound with a few turns of heavy wire which is connected in series with the circuit in which the power is required to be measured. The other two poles, *B* and *B*, in space quadrature are wound with a fine wire and are connected to the circuit so that the current through them depends upon the potential of the circuit. It is generally nec-

essary to connect in series with the latter shunt, or "potential coil," a high resistance or, preferably, a highly reactive coil.

Expression for the Torque. For the purpose of simplified mathematical discussion to determine the torque of the rotating field meter, the flux distribution in the air gap will be assumed to vary in a sinusoidal manner. Similarly, we assume that the flux from each pole varies according to the sine law, the combination of the magnetic fields from the poles BB and the poles AA, is the active torque producing field. Consider first that the circuit to which the meter is attached is non-inductive. The main current, passing through the coils AA, will produce in them an alternating flux proportional to the current since the principal

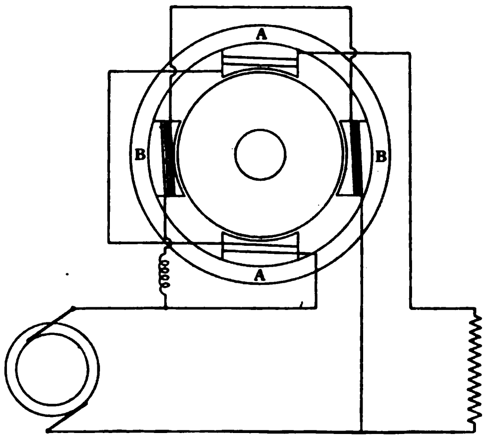

FIG. 6

part of a magnetic circuit is air, and such flux will lag slightly in time by the angle of hysteretic lead. If the shunt coils are merely connected through a pure ohmic resistance to the line wires, the currents in the coils BB will be proportional to the pressure and will lag behind the pressure by an angle dependent on the relative values of the resistance and the self-induction of the potential circuit. If, instead of simply connecting the coils by a resistance, some inductive device be placed in series, the field produced by the magnetomotive force of the pressure coil will be proportional to the applied e.m.f., but the phase angle can be so arranged that this shunt field flux is in exactly time quadrature with that due to the series coils—the necessary condition for perfect compensation.

Hence, if it may be assumed that the series field is distributed in space as the sine of the position angle around the air gap, and that its field varies according to the harmonic law with time as the independent variable we may write

$$\phi_s = \phi_s \sin \omega t \cdot \sin \theta$$

when ϕ_s is the maximum value of the flux from the series coil in the case we have under consideration, that of a non- inductive load circuit, the flux due to the shunt or potential coils will of necessity be distributed in space according to the cosine of the space angle θ, and, if the proper degree of compensation or phase adjustment has been accomplished, this flux varies as the cosine of the time-phase angle . It may be expressed as

$$\phi_p = \phi_p \cos \omega t \cdot \cos \theta$$

where ϕ_p is the maximum value of the flux.

If the load be inductive so that the current lags by an angle β behind the e.m.f., the above expressions take the form.

$$\phi_s = \phi_s \sin (\omega t - B) \sin \theta$$
$$\phi_p = \phi_p \cos (\omega t) \cos \theta$$

The field ϕ at any point within the air gap is expressed by the sum of the above equations, as:

$$\phi = \phi_s \sin [\omega t - B] \sin \theta + \phi_p \cos \omega t \,.\, \cos \theta$$

If we assume that $\beta = 2\varphi$ and choose a proper instant from which time is reckoned, we have

$$\phi = \phi_s \sin [\omega t - \varphi] \sin \theta + \phi_p \cos [\omega t + \varphi] \cos \theta$$

expanding and reducing

$$\phi = \phi_s (\sin \omega t \cos \varphi \cdot \sin \theta - \cos \omega t \cdot \sin \varphi . \sin \theta)$$
$$+ \phi_p (\cos \omega t \,.\, \cos \varphi \cos \theta - \sin \omega t \cdot \sin \varphi \cos \theta$$

$$\phi = \cos (\omega t - \theta) \left(\frac{\phi_s + \phi_p}{2}\right) \cos \varphi + \cos(\omega t + \theta) \left(\frac{\phi_p - \phi_s}{2}\right) \cos \varphi$$

$$+ \sin (\omega t - \theta) \left(\frac{\phi_s + \phi_p}{2}\right) \sin \varphi - \sin (\omega t + \theta) \left(\frac{\phi_s + \phi_p}{2}\right) \sin \varphi$$

Hence the expression for ϕ contains four terms, each representing a rotating magnetic field. For two of these expressions the maximum values occur when $\omega t = \theta$, and for the other two $\omega t = -\theta$, or in the first case we have $\frac{d\theta}{dt} = \omega$ and in the second $\frac{d\theta}{dt} = -\omega$. The combination of fields is then equivalent to four rotating fields; two rotating clockwise and two rotating counter clockwise. The maximum values of these fields are

$$\frac{\phi_s + \phi_p}{2} \cos \varphi, \text{ and } \frac{\phi_s - \phi_p}{2} \sin \varphi$$

rotating oppositely to the two fields,

$$\frac{\phi_p - \phi_s}{2} \cos \varphi, \text{ and } \frac{\phi_p + \phi_s}{2} \sin \varphi$$

If the rotor or cylindrical armature be at rest, so that the slip is 100 per cent with regard to all of the fields, each field will produce a torque proportional to the square of the maximum flux, hence, the forward torque will be proportional to

$$\frac{1}{4} [(\phi_s + \phi_p)^2 \cos^2 \varphi + (\phi_s - \phi_p)^2 \sin^2 \varphi]$$

The backward torque will be

$$\frac{1}{4} [(\phi_p - \phi_s)^2 \cos^2 \varphi (\phi_s + \phi_p)^2 \sin^2 \varphi]$$

The net torque is the difference between the forward and backward torque, and is

$$\phi_s \phi_p (\cos^2 \varphi - \sin^2 \varphi)$$

or $$\phi_s \phi_p (\cos 2 \varphi)$$

or $$\phi_s \phi_p \cos \beta$$

since $$2 \varphi = \beta$$

Hence, sin ϕ_s is proportional to the current I_s and ϕ_p is proportional to the e.m.f. E, the torque driving such a meter is proportional to the power or

$$W = I_s E \cos \beta.$$

It must be noted that when the disk is in motion the exact relations no longer hold. The "slip" of the metal disk is at all

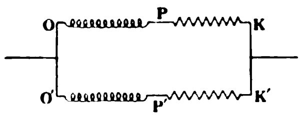

FIG. 7

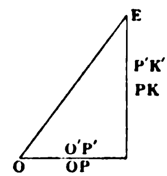

FIG. 8

times so near to 100 per cent. that the error from this source is negligible.

Compensating Devices. If we have inductance and resistance in series similar to the circuit represented in Fig. 7 and a potential E impressed on the circuit, the vector diagram Fig. 8 shows in a general way that the potential $O\ P$ and $P\ R$ add vectorially to equal the impressed pressure OE on the terminals $O\ K$. Similarly, with a parallel circuit identical with the original cir-

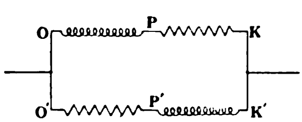

FIG. 9

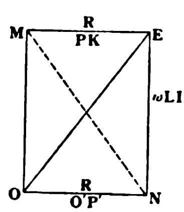

FIG. 10

cuit connected as shown in Fig. 7 as $O'\ P'\ K'$ the impressed potential $C\ E$ is resolved into two components $O'\ P'$ and $P'\ K'$ in Fig. 8, assuming that the values of the reactances and resistances are equal in the two circuits. The difference of potential between P and P' is zero in the above case but if the sequence of the reactance and resistance is reversed such that the conditions shown in Fig. 9 obtain, the resulting vector diagram, shown in Fig. 10, is slightly different and there isfound a potential

difference between P and P' given in value and relative phase by the vector MN Fig. 10. A proper choice of the reactors and resistors connected as in Fig. 9 will give a potential between P and P' at right angles to the impressed pressure, or in quadrature therewith, hence, with such an arrangement, the phase of the current in the potential circuit of the induction watt-hour meter may be governed at will. From the above elementary considerations it will become evident at once that several modifications are possible in the practical application of the principle involved to commercial meters. In point of fact, very few practical induction watt-hour meters on the market use such an elaborate circuit to obtain quadrature relations between the

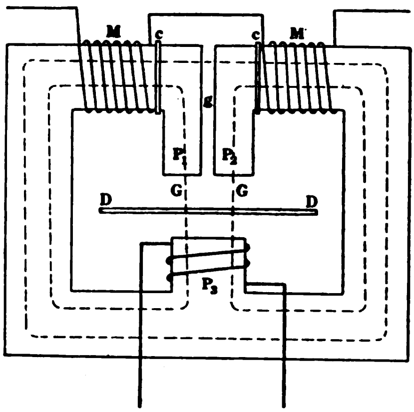

FIG. 11

potential flux and the series flux, such an extreme shifting of the phase, *i. e.* 90 deg. as here shown, is unnecessary and, in general the small amount of compensation required may be obtained by series inductors or short circuited secondary coils wound upon and over the primary potential coil. Such an arrangement as here mentioned, the short circuited secondary coil, is that employed by the shifting field motor shown in Fig. 11 at the points C C.

Shifting Field Meter. In Fig. 11 the elementary structure of the shifting field meter is given. The disk DD rotates between the poles $P1$, $P2$, $P3$ on the air gap GG. The series coil of the meter is wound around the pole $P3$. The potential coils are wound on the main frame of the meter M M'. The latter coils

are connected in series and in such a sense that the magnetic flux set up follows the paths as indicated. Due to the air gap the poles $P1$ and $P2$ are of opposite sign or $P1$ is north when $P2$ is south. If the magnetizing action of the potential coils wore absent the series coil would produce a magnetic field such that $P3$ would be of north or south polarity and $P1$ and $P2$ of south

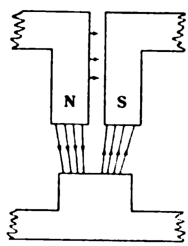

FIG. 12

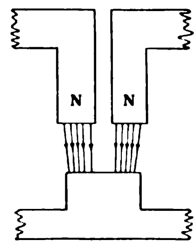

FIG. 13

or north polarity respectively. Due to the quadrature relations existing between the fluxes set up by the potential and current coils, the following sequence of polarity is obtained: In Fig. 12 the flux from the potential coil is a maximum—the current in the series coil is considered nil—hence we have pole $P1$ north and pole $P2$ south. Pole $P3$ is half north and half south. In Fig. 13 the

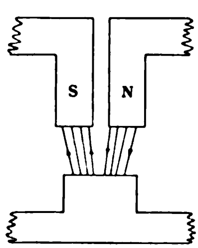

FIG. 14

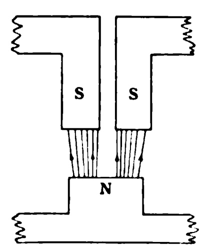

FIG. 15

flux from the potential coil has decreased and the current in the series coil having reached an appreciable positive value, pole $P1$ is still north but Pole $P2$ has been reversed due to the magnetomotive force of the series coil. In Fig. 14 the current in the potential coil is reversed, also the current in the series coil have become zero, therefore, the polarity of the poles will be as indicated *S.N.* In Fig. 15 the flux from the potential coil is again zero,

whereas the current in the series coil is a negative maximum or is flowing at its maximum rate in the opposite direction to that in which it was flowing at the instance shown in Fig. 13. The polarity of the poles is as indicated. Throughout the sequence of events outlined above for one complete cycle, it will be noted that the action in the air gap *GG* has been similar to the movement of a dense band of flux continuously from left to right as indicated by the arrows. The reaction of this moving band of flux with the eddy currents, and such small hysteretic reactions as may be present, produce a turning torque upon the disk causing rotation in the direction of magnetic shifts.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., July 1, 1915.

THIRD RAIL AND TROLLEY SYSTEM OF THE WEST JERSEY AND SEASHORE RAILROAD

BY J. V. B. DUER

ABSTRACT OF PAPER

The paper recites the details and cost of construction of the contact systems as originally installed and subsequently modified and extended, including third rail, third rail insulators, protection, joint and cross bonding, track bonding and trolley structure. Operating experiences, as creepage of third rail, sleet formation on third rail, deterioration of rail bonds and detentions to train movements chargeable to failure of these structures, are related. The cost of maintaining the various contact structures for seven consecutive years, in cost per single track mile per year, is presented. Results of actual measurement of third rail and track resistances are also given.

A DETAILED description of the route, arrangement of tracks and electrical equipment of the electrified portion of the West Jersey & Seashore Railroad has previously been published,* therefore none of this matter will be presented here.

The original contact system consisted of the following single track mileage:

THIRD RAIL.		TROLLEY.	
Main line,	127.12 miles	Main Line,	18.61 miles
Sidings,	4.61 miles	Sidings,	00.04 miles
Total,	131.73 miles	Overlapping third rail	00.91 miles
		Total,	19.56 miles

Substations are located approximately 10 miles apart and no third-rail feeders are used. The substation bus voltage is now maintained at 700. Trains of from two to seven cars are operated.

DETAILS OF CONSTRUCTION

Third Rail. The third rail throughout is of the P. R. R. Standard cross-section and composition. The rails are in lengths of 33 feet, weigh 100 pounds per yard and have a conductivity

Manuscript of this paper was received May 12, 1915.

*Electrical operation of the West Jersey & Seashore Railroad, B. F. Wood, TRANS. A. I. E. E., Vol. XXX, 1911, p. 1371.

about equal to that of a copper rod 1,200,000 cir. mil. The composition is as follows: C, 0.62 to 0.75; Si, 0.5 to 0.20; Mn, 0.80; Ph, 0.03; and S. 0.05 per cent.

Each rail joint is bonded with two copper ribbon bonds of 500,000 cir. mil. area each, concealed under special splice bars, having solid copper terminals compressed into one-inch holes drilled in the rail, as shown in Fig. 1. The rails were drilled for the bonds by hand and the bond terminals were compressed by screw compressors.

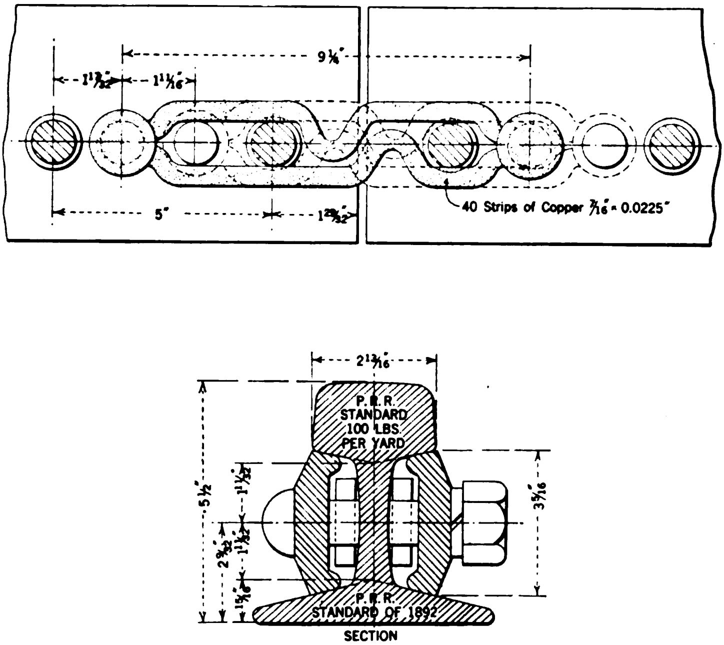

Fig. 1—Third Rail Bond Assembly and Special Splice

The third rail end approaches are made of cast iron as shown in Fig. 2. In order that no special insulator need be made to support the end approach, the bottom of which is of different shape than the bottom of the rail, a cast iron chair, Fig. 3, is used which is designed to fit the regular insulator and to center and hold the end approach thereto. The side approach, used at cross-overs, consists of a plank mounted at an angle on the side of the rail as shown in Figs. 4 and 5.

At grade crossings and other places where the continuity of the third rail is interrupted, each rail is joined electrically by a

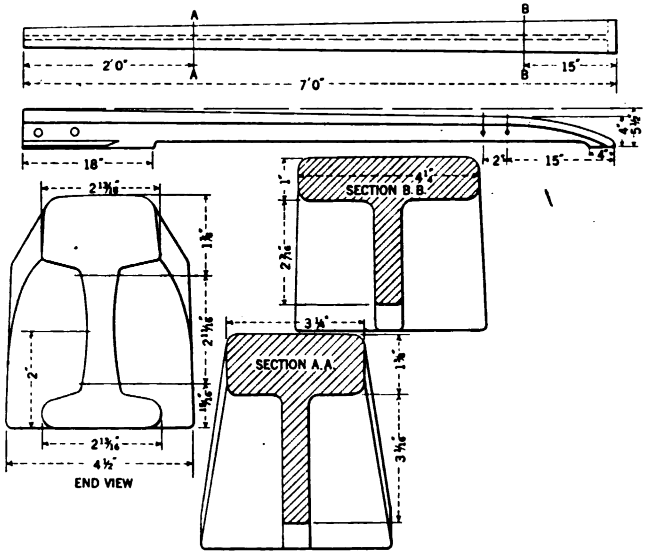

FIG. 2—THIRD RAIL END APPROACH

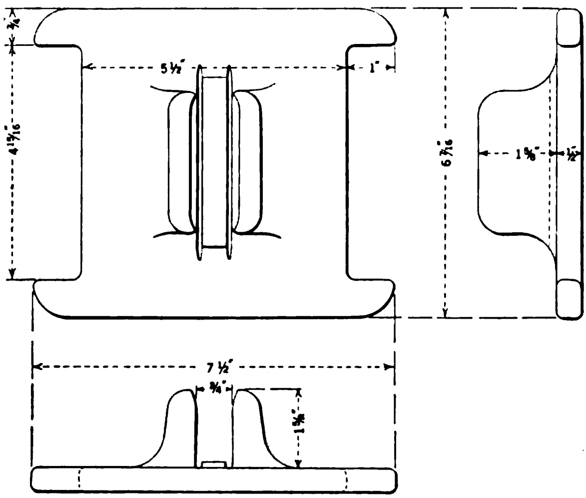

FIG. 3—THIRD RAIL END APPROACH SUPPORT

cable jumper of 1,000,000 cir. mil. area as shown in Fig. 6. The cable is drawn into a black bituminized fibre tube, which is laid in a solid concrete protection, the stub end of the cable being connected to the rail by two bare copper bonds, each of 500,000 cir. mil. area. A concrete hood fits over the top of the cable terminals.

Fig. 7 shows the relative location of third and track rails, which is the same as in the New York Terminal and Long Island Electrifications.

Insulators. The third-rail insulators used are of reconstructed

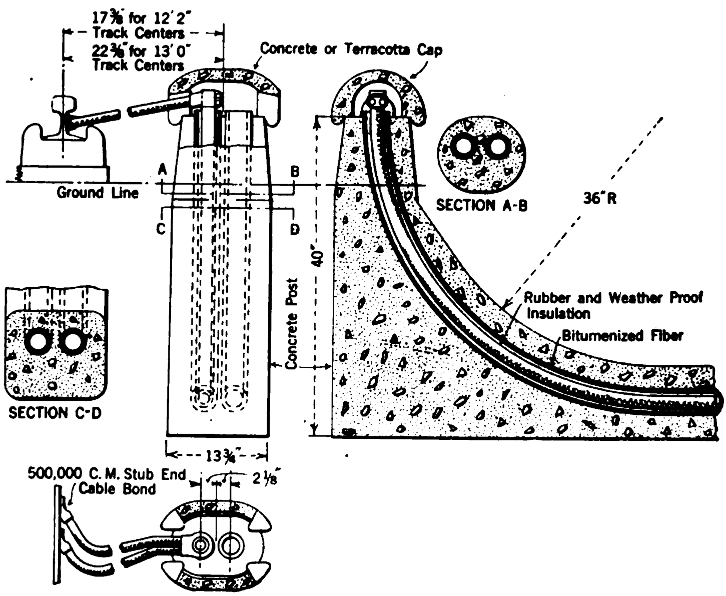

FIG. 6—SECTIONAL VIEW OF THIRD RAIL JUMPER

granite or porcelain, most of which are of the design shown in Fig. 8. They are held in position by a metal centering cup which is secured in the tie by means of a lag screw. The rail rests on the insulator and is not fastened in any way, the arrangement preventing strain on the insulators when the ties are depressed due to a passing train. The insulators are placed on ties 9 ft. 4 in. long, spaced approximately eight feet, or every fourth tie. A new design of insulator, as shown in Fig. 9, has recently been adopted because the method of supporting the top protection boards has been changed. This insulator permits of placing the protection support on the longitudinal center line of the

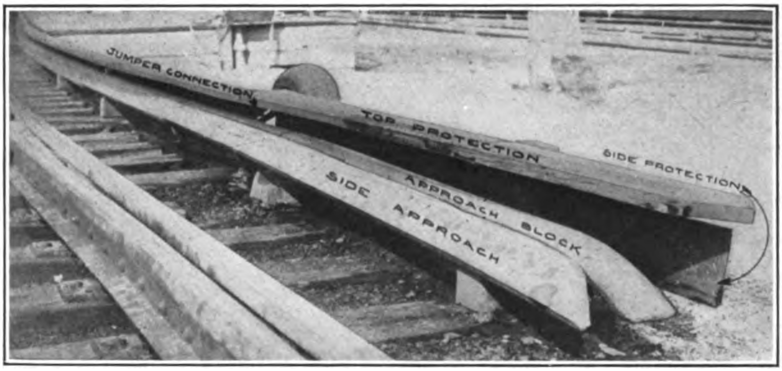

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FIG. 4—VIEW OF THIRD RAIL SHOWING END APPROACH, SIDE APPROACH AND PROTECTION

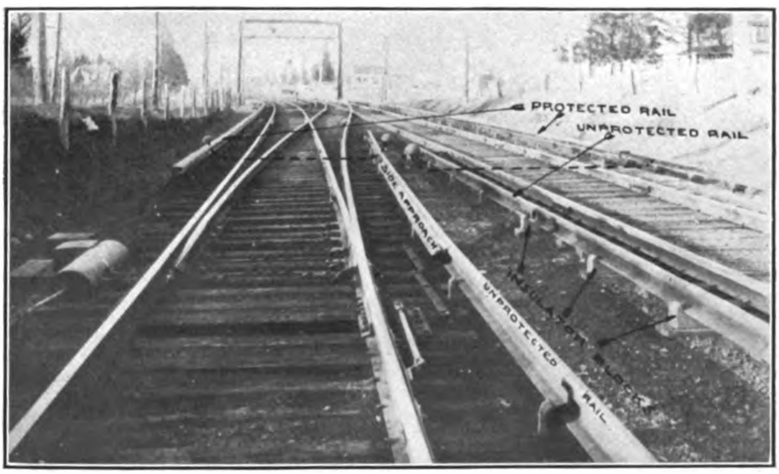

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FIG. 5—VIEW OF THIRD RAIL SHOWING ARRANGEMENT AT CROSSOVER, PRIOR TO COMPLETED INSTALLATION OF PROTECTION BOARD

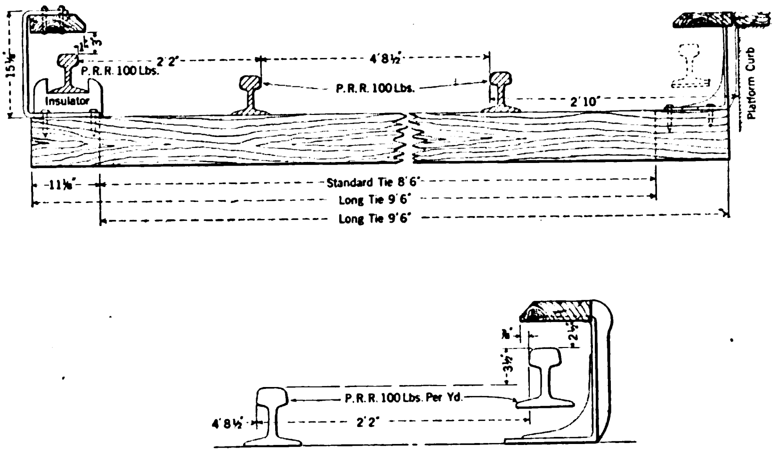
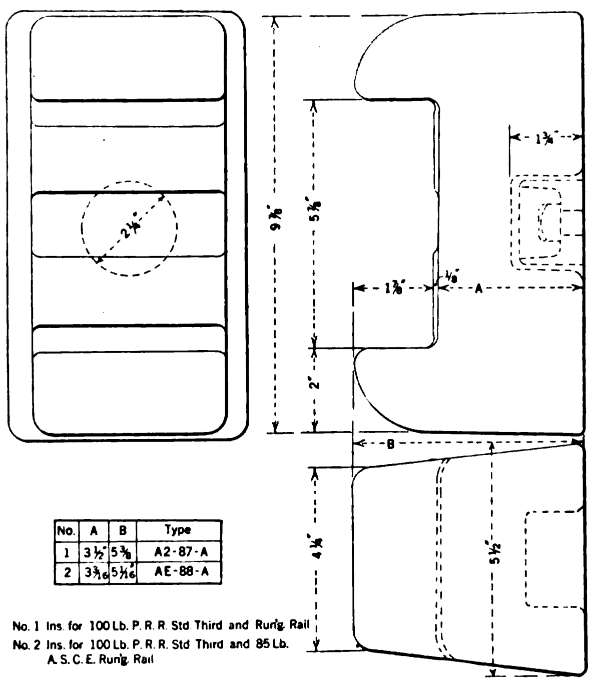


FIG. 7—RELATIVE LOCATION OF TRACK AND THIRD RAIL



No.	A	B	Type
1	3½"	5⅜	A2-87-A
2	3³⁄₁₆	5¹⁄₁₆"	AE-88-A

FIG. 8—THIRD RAIL INSULATOR—ORIGINAL DESIGN

tie, the bottom of the support with its lag screw heads forming a centering device for the insulator, as shown in Fig. 10. This insulator is used for renewals as it becomes necessary to replace the old insulators.

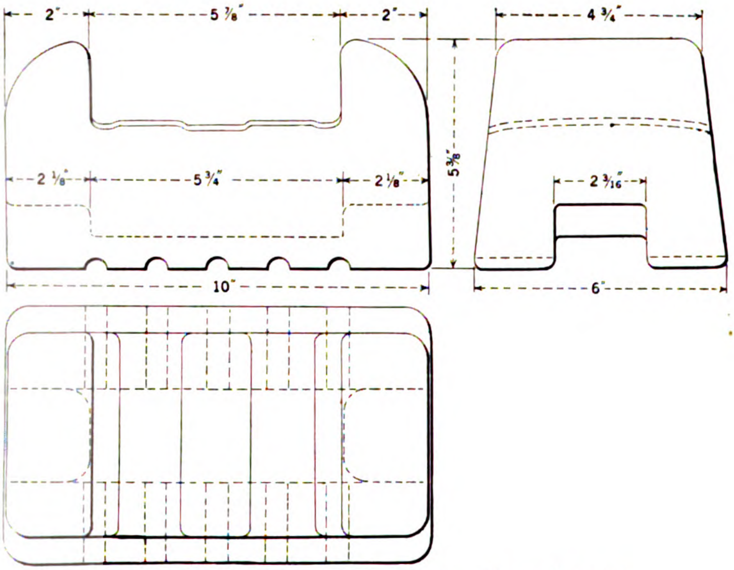


FIG. 9—THIRD RAIL INSULATOR—NEW DESIGN

Protection. Originally the third rail was equipped with protection only at stations, 75 feet on either side of road crossings and in terminal yards, and the construction was as shown in Figs. 11 and 12. The bottom casting, attached to the rail by

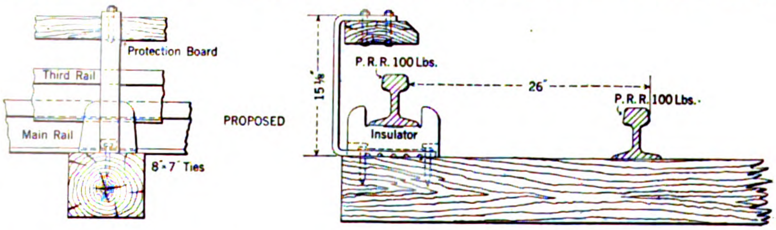


FIG. 10—METHOD OF SUPPORTING PROTECTION WHERE NEW INSULATOR IS USED

a hook bolt, which supports the whole protection structure is shown in detail in Fig. 13. A maple post, attached to the bottom casting by a bolt, supports the top casting, Fig. 14, to which are bolted the ends of adjacent top protection boards of two-inch

plank which average seven feet in length, this distance therefore being the spacing of protection supports at stations. At end approaches the top protection board extends slightly beyond the last support, therefore the top casting here is modified by eliminating a part of the vertical web, as shown in Fig. 15. The bottom casting, Fig. 16, is also modified to fit the end approach casting.

Opposite all station platforms, the rail is further protected by a plank fastened to the side of the rail. In most instances the third rail is located on the side of the track farthest from the station platform. To prevent persons on the platform from coming in contact with the contact shoes on the platform side

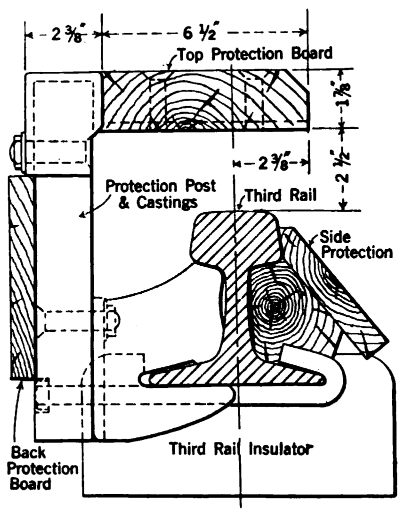


FIG. 11—THIRD RAIL PROTECTION—CROSS-SECTION

of the car, there is a protection board mounted flush with the platform and supported on castings fastened to the ties. See Figs. 17 and 7.

During the early part of 1912, top protection was added to all unprotected rail. Instead of using the old form of attachment to the rail itself, the board is supported by wrought iron brackets attached to the long ties carrying the insulators, as shown in Figs. 18 and 19. Adjacent boards are joined together by means of a wrought iron plate. The wood used in the original protection was not treated in any way but was given several coats of paint after installation; that used in this latter installation was given two coats of hot creosote.

Trolley Wire. Originally, a trolley wire of span type construction was used instead of third rail between Newfield and Millville, 10 single track miles, and between South Gloucester and Haddon

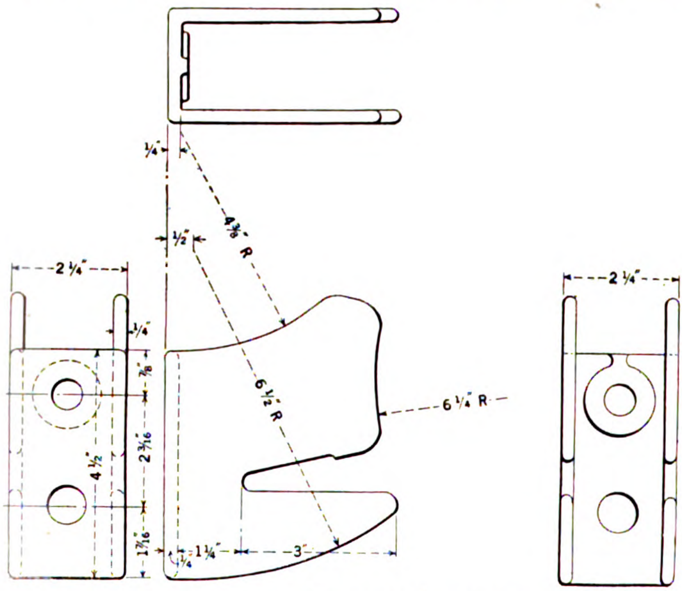


FIG. 13—THIRD RAIL PROTECTION—BOTTOM CASTING

Avenue, Camden, 9.56 single track miles, on account of these districts being thickly settled and the tracks at grade, but in March, 1910, the trolley wire on the Millville Branch was replaced

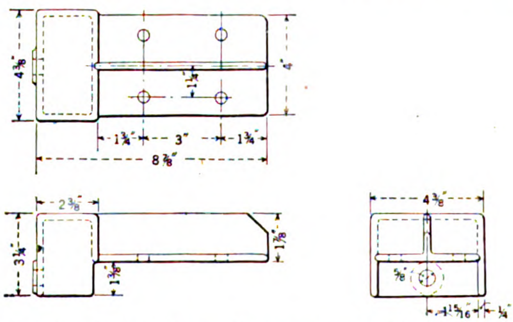


FIG. 14—THIRD RAIL PROTECTION—TOP CASTING

by third rail of the same construction as that of the rest of the road. The trolley wire is No. 4/0 grooved section, supported by $\frac{3}{8}$ inch galvanized steel stranded span wires at a height of

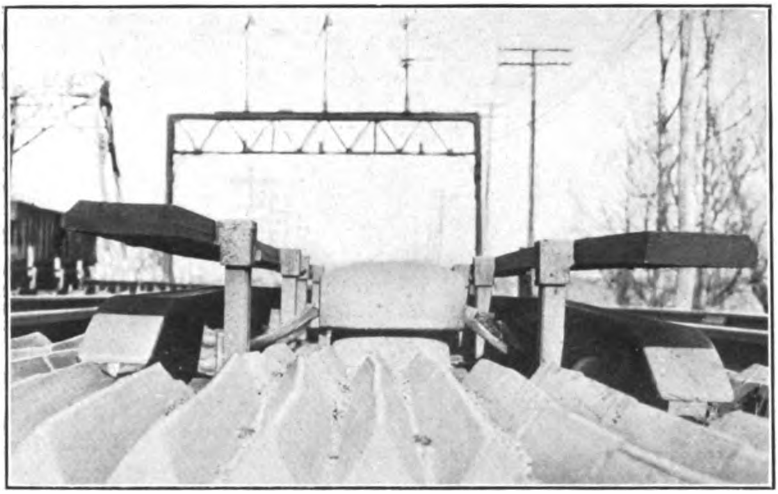


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FIG. 12—VIEW SHOWING ORIGINAL PROTECTION, END APPROACH AND CABLE JUMPERS

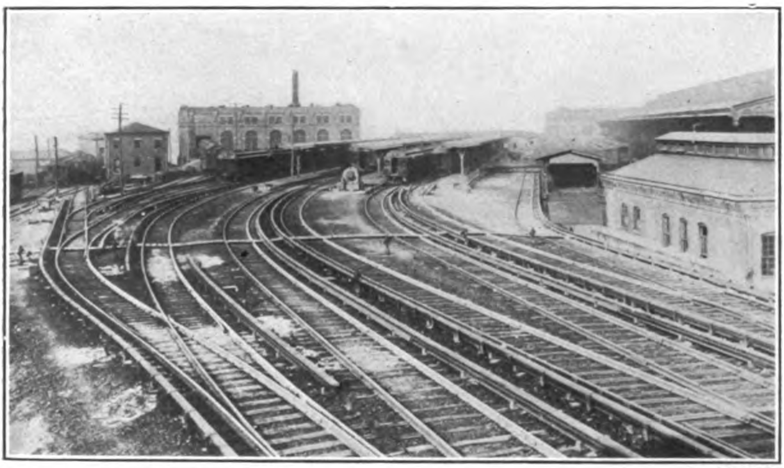

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FIG. 22—VIEW OF CAMDEN YARD

22 feet above track rails. The supporting poles are mostly of wood and are spaced at a distance of 100 feet. Through Camden, tubular steel poles are used and, wherever practicable,

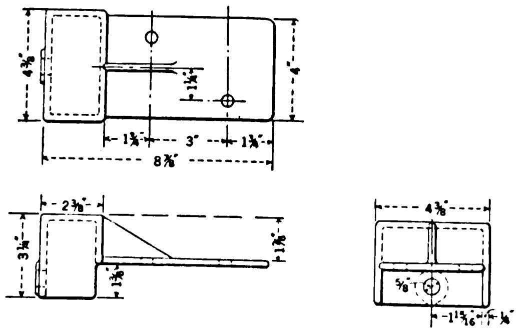

FIG. 15—THIRD RAIL PROTECTION AT END APPROACH—TOP CASTING

the high tension transmission poles are used as supports. There are two 750,000 cir.mil. feeders between South Camden Substation and Haddon Avenue, Camden, and one 500,000 cir. mil. feeder

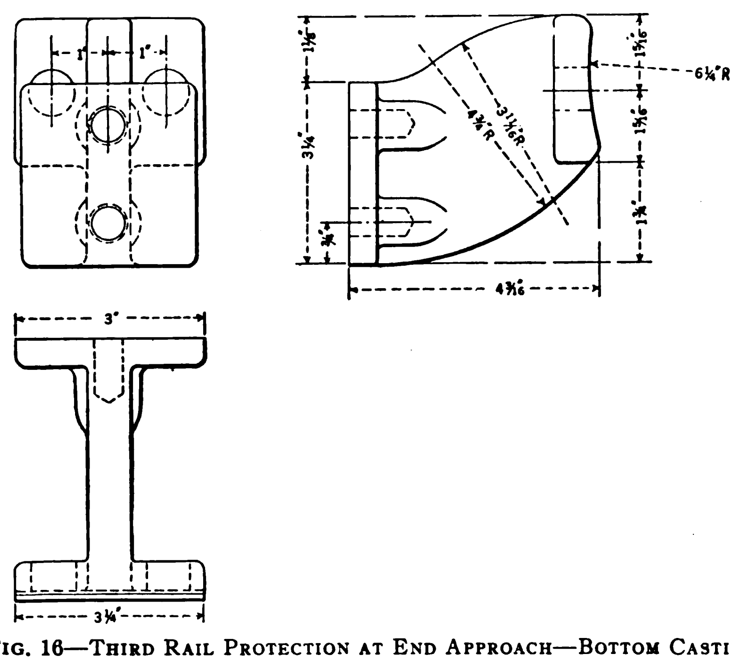

FIG. 16—THIRD RAIL PROTECTION AT END APPROACH—BOTTOM CASTING

between South Camden substation and South Gloucester. The feeder formerly used between Newfield and Milville was 750,000 cir. mil. area. Multi-gap lightning arresters are installed

approximately 1000 feet apart. All pull-offs, strain ears, feeder ears and splicing sleeves are of bronze and of standard pattern.

Track Bonding. The track rail joints are bonded similarly

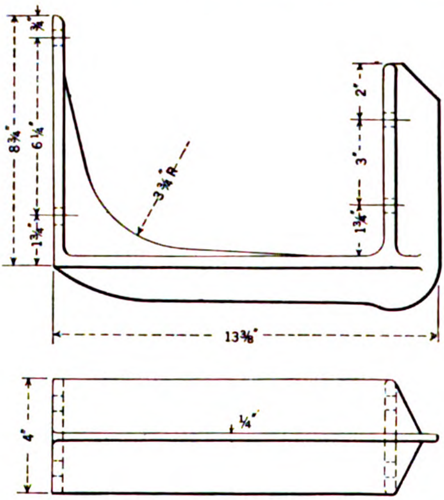

Fig. 17—Platform Protection Support

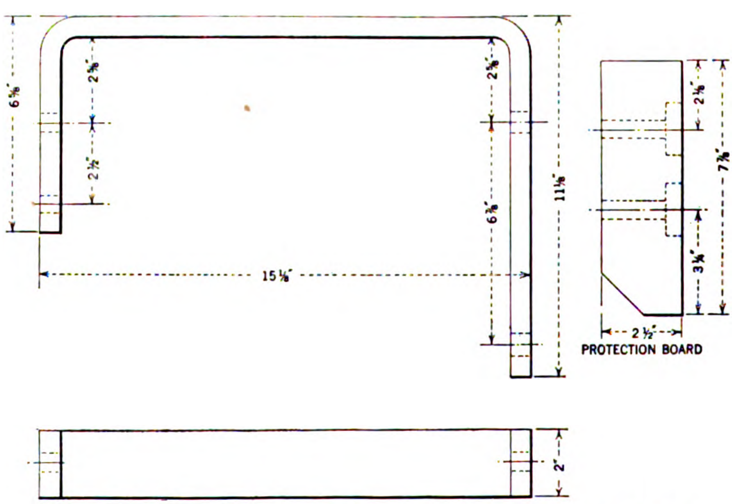

Fig. 18—Detail of Third Rail Protection Bracket

to those of the third rail except that two bonds of 400,000 cir. mil area each are used. Bonds composed of 40 copper ribbons, 7/16 in. by 0.0225 in. were originally used, but experience showed that the ribbons were too readily broken close to the

terminals due to the vibration of the joints, therefore stranded wire bonds of the same total area are now used with greater success. The original bonding was done without interruption to traffic and all holes were drilled by hand, one splice bar being kept in position to provide for the safe passage of trains.

Third Rail Cross-Bonding. Opposite each substation a wood insulating block is inserted in the third rail of each track, thus

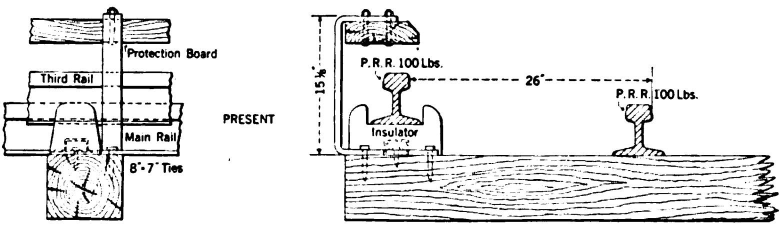

FIG. 19—GENERAL ARRANGEMENT OF PROTECTION ADDED IN 1912

sectionalizing the third rails at these points. Originally the third rails of all tracks were electrically connected together midway between substations through fused sectionalizing switches, normally kept closed to obtain the combined conductivity of all rails, so arranged that any of the four sections could be disconnected from the rest of the system in the event of trouble or heavy repairs. So little trouble with the third rail

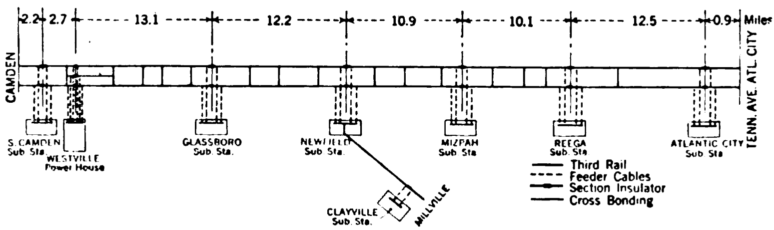

FIG. 20—THIRD RAIL DIAGRAM SHOWING CROSS-BONDING

has been experienced, however, that there was no advantage attached to the sectionalizing feature and the switches were therefore removed and the third rails were permanently bonded together at this point and at two other points between most of the substations, as shown in Fig. 20, to obtain greater conductivity. In terminal yards where there is more likelihood of third rail trouble, the rails of the various tracks are fed through fuses and sectionalizing switches, so that if trouble

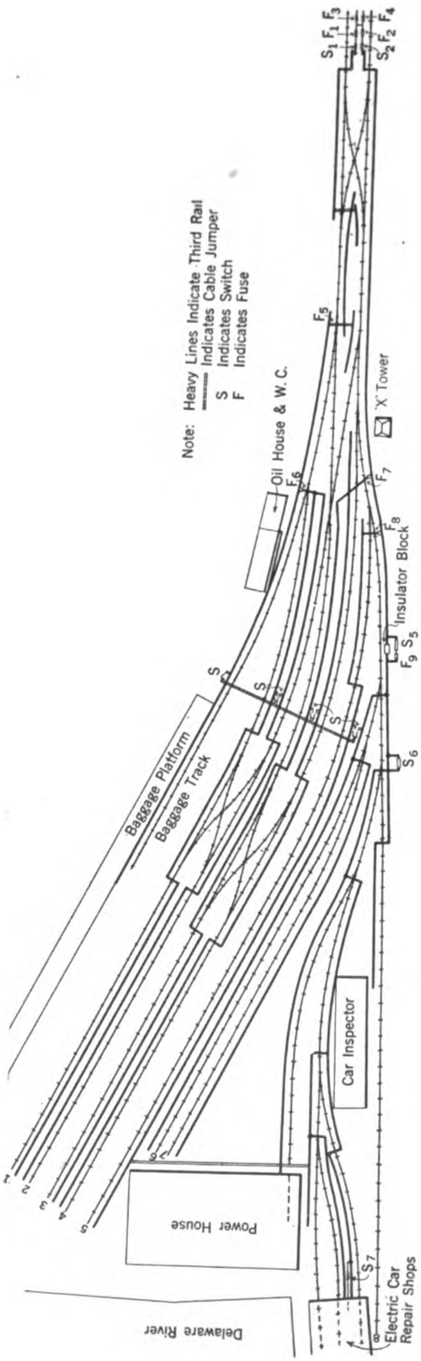

FIG. 21—THIRD RAIL SECTIONALIZING SWITCHES IN CAMDEN YARD

develops on one track, that section of the yard can be isolated from the rest. The arrangement in Camden Yard is shown in Figs. 21 and 22. The fuses here are of 1600 ampere capacity.

Cost of Construction

The original cost of construction was as follows:

	Miles	Total cost	Per mile
Third rail, including rail, bonding, insulators, protection, etc.	131.73	$557,636.00	$4,235.00
Trolley wire, including wire, poles, line material, lightning arresters, etc.	19.56	80,500.00	4,120.00
Track bonding	151.29	102,659.00	678.50

The cost of replacing the trolley wire with third rail between Newfield and Millville is given in Table No. 1.

Operation and Maintenance Experiences

Shortly after the third rail was placed in service it began to creep in the direction of traffic, with attendant tightening and straining of the jumper sub-end bonds and breaking of insulators. The insulator ears were broken off on curves by the buckling of the rail and on tangent track by the strain imposed upon them when the protection supports, attached to the rail were brought against the insulators when creepage occurred. To overcome the difficulty, the third rail was anchored to the ties at intervals of from 1000 to 1500 feet and the practice of periodically loosening the splice bars and oiling the joints was instituted. This eliminated the creepage, but the anchors frequently gave trouble by breaking down in insulation, causing delays to traffic, when it was found that the loosening and oiling of the joints in itself gave satisfactory results and all the anchors were removed. The joints are now oiled by the patrolmen every Spring and Fall. The protection added in 1912 was held by supports attached to the ties, as previously explained, thus holding it stationary and independent of the movement of the rail.

Although sleet-cutting shoes were used on the cars during seasons when sleet was likely to form, with the provision of an extra tension device for applying a tension on the shoe of from 90 to 100 pounds, considerable trouble was occasioned by sleet, resulting in numerous delays to traffic. Cars specially

fitted with calcium chloride tanks, with means for heating same and distributing on the rail while hot, are hauled over the road by steam locomotives when sleet begins to form and this minimizes trouble as much as practicable. The addition

TABLE NO. 1.

COST OF REPLACING TROLLEY WITH THIRD RAIL BETWEEN NEWFIELD AND MILLVILLE.

		Cost	
		Total	Per mile.
Third Rail,			
Labor	$ 1,805.48		
Material,	24,736.92		
Freight, etc.,	171.30		
		$26,713.70	$2,534.64
Splices,			
Labor	$ 5.00		
Material,	1,155.59		
		1,160.59	110.50
Bonding,			
Labor,	$ 1,109.19		
Material,	3,318.20		
Freight,	64.50		
		4,491.89	427.80
Insulators,			
Labor	$ 175.24		
Material,	2,153.05		
		2,328.29	221.74
Long Ties,			
Difference between cost of long and standard ties,		1,863.20	177.50
Total		$36,557.67	$3,481.68
Cable Jumpers,			
Labor,	$ 927.00		
Material,	2,914.77		
Freight,	29.80		
		$ 3,871.57	$ 113.87 Per Crossing
Protection (Road Crossings and Stations only)			
Labor,	$ 497.59		
Material,	1,953.91		
Freight,	108.06		
		$ 2,559.56	0.1347 Per foot
Long Ties,			
Substituting for short ties,			
Labor	$ 2,065.00	2,065.00	196.50 per mile

of the top protection to the rail overcomes sleet formation in a great many cases but is of little use in this respect when a driving wind accompanies sleet forming weather, in which event the chloride cars are used as formerly.

The trolley wire is given rigid and frequent inspection to locate defects before failures occur. The maintenance cost is about six times that of the third rail, as may be seen by reference to the table under the heading "Maintenance Costs."

Third-rail bonds require practically no attention as tests indicate little change in their resistance. Road crossing jumpers gradually deteriorate and occasionally develop defective insulation and burn out. Due to the vibration of the track rails at joints, the track bonds require testing and partial renewal every six months. Any joint showing a resistance equivalent to eight feet of rail or over is marked for rebonding. The following table shows the results of a number of track bond tests.

Date	Joints tested	Joints defective	Per cent defective
October, 1909	46,633	716	1.53
May, 1910	46,633	378	0.81
October, 1910	46,633	381	0.82

The testing is done by three men working together, and between 5000 and 6000 joints can be tested in 10 hours.

Maintenance Costs

The cost of maintaining trolley, third rail and track bonding systems for the past seven years is given in Table No. II. The maintenance cost of each system includes the amounts directly chargeable to that system and a pro rata charge for general expenses as follows: Superintendence; Maintenance, Labor and Material; Tools and Supplies; Proportion of Expense of Purchasing Department; Telephone Operation; Stationery and Printing; Tower Car Service for Trolley; Operation of Chloride Cars for Third Rail; and Bond Testing for Track Bonding. Credit is applied for all scrap material of value. The average maintenance cost per mile per year is also expressed in per cent of the construction cost per mile.

Train Detentions Chargeable to Contact Systems

Summary reports showing train detentions for all causes are not regularly prepared; such reports for the years 1909 and 1912, however, are available and show the detentions chargeable to the contact system as given in Table No. III.

TABLE NO. II

WEST JERSEY AND SEASHORE RAILROAD ELECTRIC TRAIN SERVICE

MAINTENANCE COST PER SINGLE TRACK MILE PER YEAR.

Year	Trolley	Third rail	Track bonding
1908	$424.25	$53.52	$15.74
1909	391.81	71.23	21.18
1910	510.44	76.65	15.28
1911	376.05	111.99	17.46
1912	642.44	99.10	21.47
1913	636.10	86.16	44.95
1914	450.67	73.54	44.82
Average	$490.25	$81.74	$25.84
Per cent of investment per mile	11.90	1.93	3.77

TABLE NO. III.

WEST JERSEY AND SEASHORE RAILROAD ELECTRIC TRAIN SERVICE.

TRAIN DETENTIONS CHARGEABLE TO CONTACT SYSTEMS.

YEAR 1909.

Single Track Miles of Third Rail, 131.73; Single Track Miles of Trolley 19.56.

	Number detentions		Minutes detentions		
	Total	Per cent of total for all causes	Total	Per cent of total for all causes	Car miles per minute detention
Third rail short circuits	3	0.032	14	0.031	293,340.40
Third rail out of place	1	0.011	8	0.019	513,345.13
Third rail anchor on fire	1	0.011	5	0.011	821,353.00
Third rail protection out of place	1	0.011	1	0.002	4,106,765.00
Sleet on third rail	47	0.510	812	1.818	5,057.59
Trolley wire trouble	253	2.742	1920	4.299	2,138.94
YEAR 1912. Single Track Miles of Third Rail, 141.73; Single Track Miles of Trolley 9.56.					
Third rail short circuits	14	0.189	82	0.314	56,673.61
Third rail out of place	1	0.014	4	0.013	1,161,809.00
Third rail protection out of place	1	0.014	20	0.075	232,361.80
Sleet on third rail	43	0.581	391	1.509	11,885.51
Trolley wire trouble	48	0.649	272	1.049	17,085.43

Sleet troubles vary considerably during different years, and all detentions due to this cause may occur on one day. The detentions chargeable to the trolley wire are frequent and more or less regular. In addition to the detentions from this cause given in Table No. III, are the following:

Year	Single track miles of trolley	Detentions	
		Number	Minutes
1908	19.56	230	2864
1910	9.56	63	927
1911	9.56	46	165

Third Rail and Track Resistances

Resistance of third and running rails, measured by the drop of potential method, are given in Table No. IV. The tests were made directly after the rail bonds had been tested and defective ones renewed. Where total resistance of third rails and running tracks was measured, the current flowed the length of the third rails, in multiple, and returned through the running rails, in multiple.

TABLE NO. IV

WEST JERSEY AND SEASHORE RAILROAD ELECTRIC TRAIN SERVICE

Third Rail and Track Resistances.

No. of continuous rails measured		Length of section measured in miles	Weight of rails pounds per yd.		Ballast	No. of third rail jumpers on sect.	Weather	Total res. in ohms	Res. per mile single rail in ohms	Total res. per mile of single track with third rail
Running (In multiple)	Third (In multiple)		Running	Third						
6	0	3.4	100	...	Stone	. .	dry 42°F	.02607	.0460	.....
4	0	9.0	100	...	Stone	. .	" "	.07730	.0344	.....
0	3	3.4	...	100	. .	28	" "	.04989	.0440	....
0	2	9.0	...	100	...	46	" "	.23520	.0523	....
2	1	8.1	100	100	Stone	20	wet "	.33628	....	.0415
4	2	10.9	85	100	Cinder	50	" "	.35172	....	.0645

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., July 1, 1915.

OVERHEAD CONTACT SYSTEMS, CONSTRUCTION AND COSTS

PART I

BY E. J. AMBERG

ABSTRACT OF PAPER

This paper, written with special reference to the New Haven electrification, gives a brief analysis of the systems and points to be considered in equipping trunk lines with overhead catenary construction. The paper is sub-divided into five parts, viz: catenary systems, supporting structures, sectionalization, special construction and cost data.

Under "Catenary Systems" a short description is given of the various types used on the New Haven, stating the conditions for which each is best adapted.

The same applies to the supporting structures and sectionalization.

Under "Special Construction" only the cross-overs and river crossings have been considered more fully, while other special work has only been mentioned, as it was not within the scope of this paper to go into the details of construction.

With reference to the cost data: It should be borne in mind that the figures given apply to the New Haven construction which was installed in the section with greatest traffic density, also through thickly settled communities. Therefore, the figures given will be of little value for comparison or estimating unless these conditions are equated.

THIS SECTION of the paper is written with special reference to the electrification of the New York New Haven & Hartford Railroad between New York and New Haven, the New York Westchester & Boston Railway, and of the Hoosac Tunnel section of the Boston & Maine Railroad; the writer having been closely associated with this work under the direction of Mr. W. S. Murray.

The N. Y., N. H. & H. R. R. section covers an entire engine district consisting of 75 route miles of four and six-track main line; six route miles of single track branch line; large freight yards, station sidings and industrial spurs. The New York Westchester & Boston Railway section consists of 17½ route miles of four and two-track main line with yards and sidings. The Boston & Maine Railroad section consists of eight route miles

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of double track with yards and sidings, and includes a tunnel section of 4.75 miles. These electrifications total 575 miles on a single track basis. Several types of catenary construction were necessary to meet the various requirements.

For convenience, the paper is sub-divided into the following general parts. (1) Catenary Systems. (2) Supporting Structures. (3) Sectionalization. (4) Special Construction. (5) Cost Data—General.

Catenary Systems

A catenary system may be either rigid or flexible, but the two should never be combined, for operating experience has shown that where flexible and rigid parts meet, trouble is especially liable to occur. The flexible system has been most used in this country and three distinct types have been installed on the New Haven and its allied lines, viz: double catenary, compound catenary and single catenary.

Double Catenary. This was the pioneer catenary installation in the world as applied to trunk lines with heavy traffic density. When installed it was considered necessary to provide stiffness against wind to keep the trolley within reach of the locomotive pantagraphs. Two 9/16-inch steel messenger strands were used, to which triangular hangers were fastened, these supporting the copper trolley wire. This provided horizontal stiffness and vertical rigidity; thus the construction was a combination of a rigid and flexible system, the rigid section being the two messengers with triangular hangers, the flexible part the copper trolley wire between hangers. Initial operation showed that this combination was not adapted to high-speed service and it was readily changed to a flexible system by the addition of a steel trolley wire supported by clips from the copper conductor. These clips were installed midway between triangular hangers. (This phase of the construction has been thoroughly discussed in Mr. Murray's paper "The Log of the New Haven Electrification.") The double catenary system also has the advantage that if one messenger broke the other would prevent the catenary from falling.

The system has several disadvantages. On account of the two live messengers being carried over the bridges, it is impossible to do work on the trusses, such as installing signals or running taps from one side to the other, without having power cut off. No ground wires were installed, as it was thought that

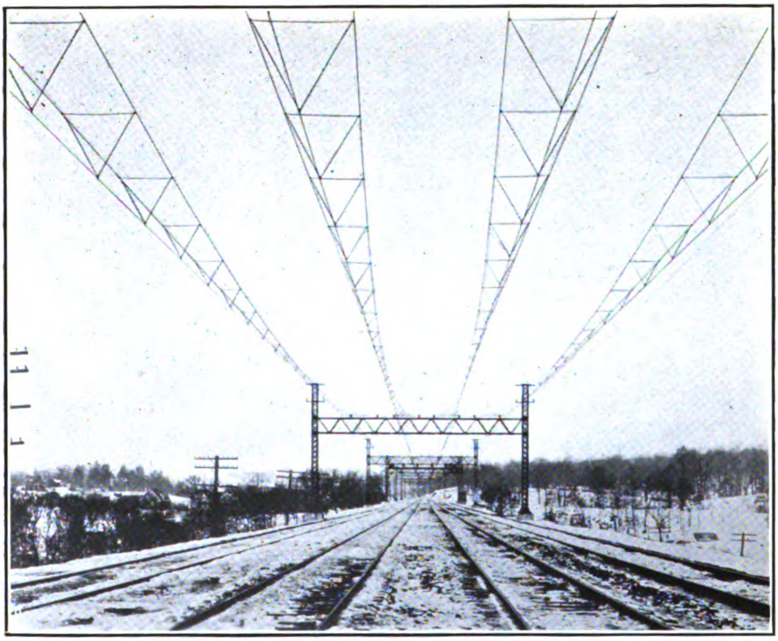

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FIG. 1—DOUBLE CATENARY INSTALLED ON ORIGINAL NEW HAVEN ELECTRIFICATION BETWEEN WOODLAWN AND STAMFORD

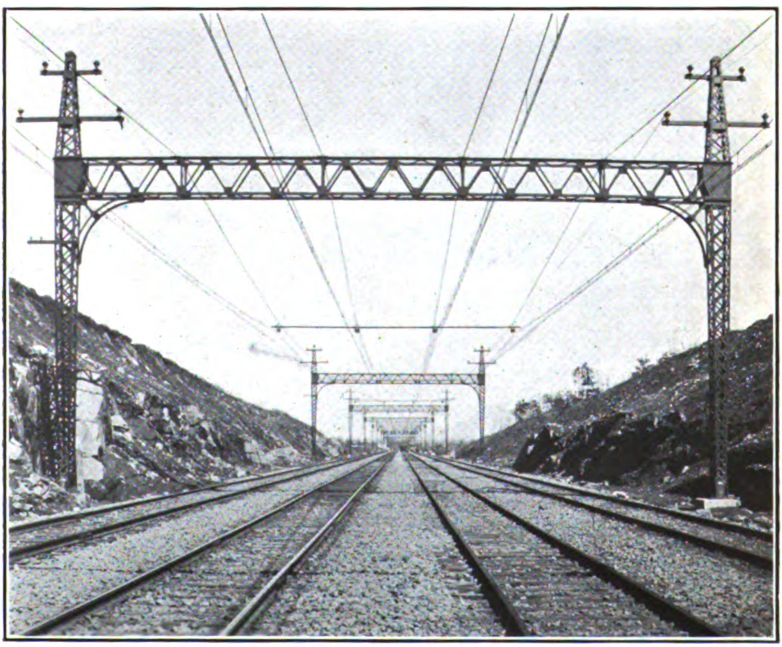

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FIG. 2—COMPOUND CATENARY ON FOUR-TRACK TANGENT SECTION

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FIG. 3—COMPOUND CATENARY ON SIX-TRACK SECTION, SHOWING ALIGNMENT ON REVERSE CURVE

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FIG. 4—SINGLE CATENARY ON FOUR-TRACK TANGENT SECTION

lightning arresters of the spark-gap type would be adequate to prevent trouble from lightning; but the protection was insufficient, and electrolytic lightning arresters have now replaced them. The trouble from lightning has been reduced considerably but is still greater in this section than on any other part of the electrification.

Compound Catenary. This was first developed and installed on the one-mile section at Glenbrook, Ct. The type was further developed and applied to the Harlem River Branch, the New York Westchester & Boston and the section between Stamford and New Haven. It was considered desirable to install a grounded messenger over each track, which would remove the live parts of the catenary from the trusses, eliminate lightning trouble and at the same time be used to keep the trolley wires nearly over the center line of track without the use of pull-off poles. The $\frac{7}{8}$-inch messenger is carried over the catenary bridges and is supported on cast iron saddles instead of insulators as in the double catenary type, and is thereby grounded to the bridges. These messengers, strung over each track, are connected at the quarter points of the spans by three-inch I-beams running across tracks. The suspension insulators are attached to these I beams for carrying the single catenary, which consists of a $\frac{5}{8}$-inch stranded steel messenger clamped to the insulators a 4/0 copper conductor supported from the strand by $\frac{1}{2}$-inch rod hangers every 10 ft., and a 4/0 steel contact wire fastened to the copper conductor by clips placed half way between the rod hangers. On curves the " Murray " hanger is used. This is clamped to the messenger and is held at a suitable angle by the acting forces. Fastened to the lower end is a duplex clip to hold the copper and steel trolley. Length and angle of hanger are adjusted so that the clips are true to line and the contact wire is held over the center of track. With this type of construction it is possible to maintain 300 ft. spans on curves up to three degrees without pull-offs; for sharper curves it is necessary to shorten the spans. Even on reverse curves no difficulty has been experienced in keeping the contact wire in its proper location. On curves above two degrees, the temperature has an influence on the alignment of the contact wire, requiring the use of pull-offs spans between bridges.

Single Catenary. In this construction the insulators are attached to the under-side of the trusses and the single catenary suspended from them. This also keeps the live wires of the

catenary below the steelwork. For tangent sections the bridges can be spaced 300 ft., but for curves this distance must be reduced unless pull-offs are used. Adequate lightning protection was secured by stringing ground wires on the feeder supports.

Single catenary may be used both for main line and yard work. In yards the copper wire may be omitted for the reason that in the average yard the trolley wires have sufficient current carrying capacity, since several tracks are connected in multiple.

To make the yard construction as light as possible, a $\frac{3}{8}$-inch messenger, 2/0 trolley and $\frac{3}{8}$-inch hangers were used, except for tracks with frequent movements; these were equipped with $\frac{5}{8}$-in. messenger, 4/0 trolley wire and $\frac{1}{2}$-inch rod hangers.

Contact Wire. The steel trolley wire rusts considerably; this rust is washed off by rain and drips onto coaches and locomotives operating in the zone, making them unsightly and necessitating more frequent painting. Where frequent locomotive movements are made, the under-side of the trolley wire is kept bright and presents a good collecting surface, but where locomotives are operated infrequently rust collects, causing increased sparking and burning of pantagraph shoes. In the Woodlawn-Stamford section the steel trolley wire has been in service since 1907 and at points of greatest wear phono-electric trolley wire has been installed, with very satisfactory results. For future electrifications doubtless steel contact wire will be less used, although the difference in first cost is much in favor of it.

Insulators. Insulation is a very important part of any catenary system, and the slight additional cost for insulators with a high factor of safety is good insurance. The types used on the New Haven electrification were all tested for 110,000 volts. The pin, suspension, and some of the strain insulators are of the porcelain type; other strain insulators are of wood. Temperature strains in porcelain insulators should be given most careful consideration, especially in the dead-end type. Failures have been caused by steam train operation in the electrified zone, break-downs being most frequent where clearance between the locomotive stack and insulator is restricted, or where steam engines stopped under or near an insulator. Where clearances are restricted it is advisable to locate the insulators off the center line of track or to use two insulators in parallel, spaced several feet apart. In tunnels two insulators in series

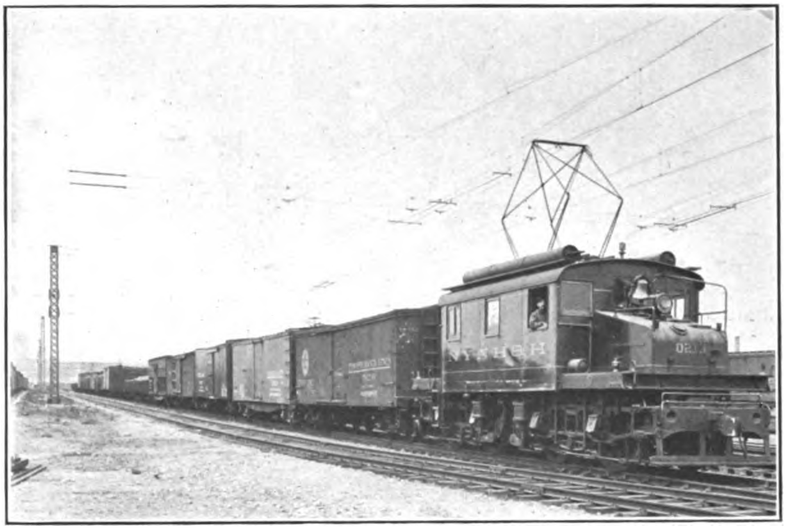

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FIG. 5—CATENARY CONSTRUCTION FOR LARGE YARDS

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FIG. 6—HOOSAC TUNNEL ELECTRIFICATION SHOWING LIGHT CATENARY BRIDGES AND DOUBLE INSULATION IN TUNNEL

are advisable and this form was successfully used in the electrification of the Hoosac Tunnel; in this case each insulator was tested for 150,000 volts (Fig. 6).

Supporting Structures

The supporting structures can be divided into three classes; bridges, steel or wood poles with cross-spans, and poles with brackets. Choice of the supporting structure is governed by the load to be carried, number of tracks to be spanned, right-of-way available, factor of safety desired and other conditions. On the New York New Haven & Hartford Railroad and New York Westchester & Boston Railway systems the supporting structures for the main line tracks were designed not only to carry the catenary system, feeders and transmission lines, but also a signal over each track weighing 2400 lb.

A bridge was the only structure which would fulfil the above conditions. On the New Haven electrification between Woodlawn and Stamford the bridges are designed so that all overturning moments were taken at the base, a feature which required large foundations. The bridges for the Harlem River Branch, New York Westchester & Boston and the main line between Stamford and New Haven were designed to take the moments resulting from stresses acting across track in the corner connections between posts and truss. The foundations have only to resist the over-turning moment along and the shear across track, making them much lighter than those first installed. The cost of the combined structure is materially reduced by having the steelwork carry the stresses. The height of the bridges is regulated so as to keep the contact wire 22 ft. above the top of rail, excepting at places where clearance is restricted. These bridges span six tracks on the Harlem River Branch, four tracks on the main line and a section of the New York Westchester & Boston, and two tracks on the New Rochelle and White Plains Branch of the N. Y. W. & B. Ry. Some special bridges span as many as ten tracks.

The cross-span construction is especially well adapted where a large number of tracks are to be equipped with single catenary. This applies to main line as well as yards. The cross-span messenger is supported by poles, which may be either self-supporting or guyed. On the New Haven electrification most structures are self-supporting. The cross-span construction was used in all yards and at certain points for main line work.

The cross-span messengers of $\frac{7}{8}$-inch or $\frac{5}{8}$-inch steel strands are supported by latticed steel poles in large, and by wooden poles in small yards. Pull-offs cannot be entirely avoided in yard work on account of sharp curves. The cross-span being a flexible support, makes necessary the use of steady strands to hold the catenary in its proper position over the tracks.

Poles with Brackets. This type has been used for single track sections and for station and industrial sidings. It is cheaper but not so reliable as the others, although suitable for the purpose. 150 ft. is about the longest span which can safely be used on tangents with wooden poles.

Sectionalization

It is necessary to sectionalize the contact system to locate trouble and to make repairs with the least interference to operation. Main line tracks should be sectionalized from each other and each should again be divided into sections. The sectionalizing points should preferably be at or adjacent to principal cross-overs, which are generally controlled from signal towers. There are always employees at such places, who may be charged with the small additional duties of operating the electrical apparatus. To disconnect a defective section quickly, automatic oil circuit breakers are used. These breakers should be of ample size and staunch construction as they are subject to a severe service. The automatic opening of breakers is controlled by relays, with enough margin for adjustment to insure proper selection and sequence of operation. On the New Haven and the New York Westchester & Boston Railway systems, the breakers are of the outdoor type mounted on sectionalizing bridges. This gives the shortest possible high-tension connection between busses, track catenaries, feeders and these circuit breakers. The switchboard, with the control switches and relays, is located in the signal tower. The connections between the board and the breakers are made by means of individual lead-covered cables. Under certain conditions a better layout can be obtained by placing indoor type circuit breakers in a building beside the track. Such an installation was made by the engineers of the New Haven when electrifying the Hoosac Tunnel of the B. & M. R. R.

The actual break or gap in the track catenaries can be made in different ways. Two distinct types, however, with various modifications were used on the New Haven; one rigid, the other

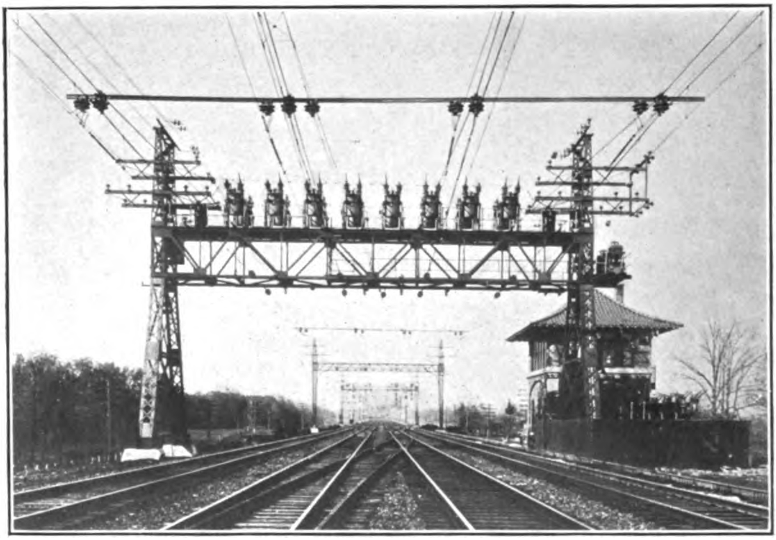

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FIG. 7—TYPICAL SECTIONALIZING BRIDGE ON FOUR-TRACK SECTION

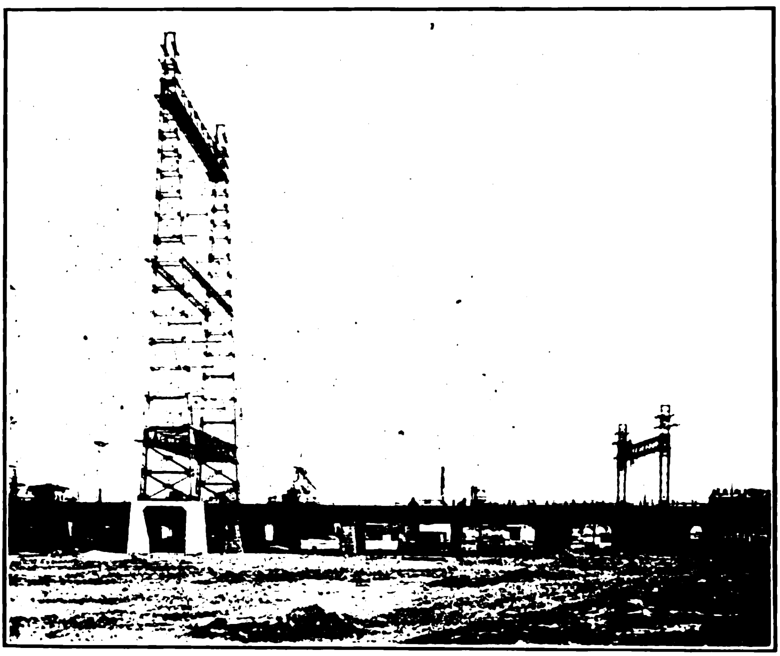

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FIG. 9—TYPICAL RIVER-CROSSING TOWER

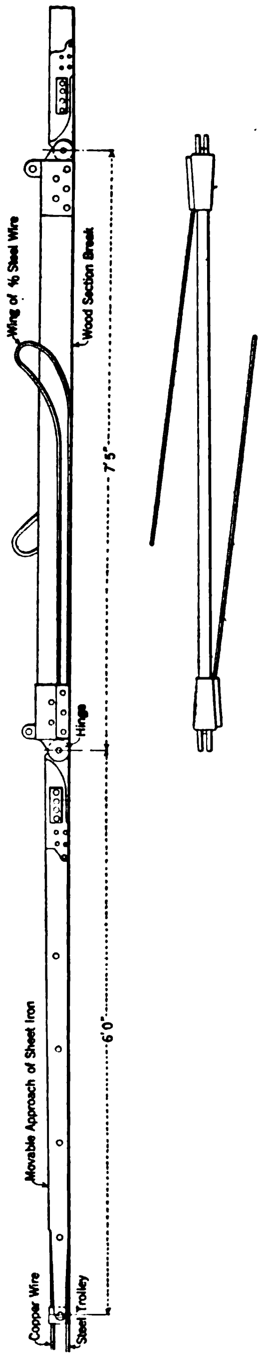


Fig. 8—Wood Section Break

flexible. The rigid type was a wood section insulator, which gives a very simple construction but produces an undesirable hard spot for high speed operation. By installing a movable approach to the wood section break, the effect of the hard spot is somewhat reduced. The flexible wings shown on the wood section break (Fig. 8) are arranged to prevent an engine from getting stalled at that point.

In the flexible type, air is used as an insulating medium; insulation is obtained by having the trolley wires of the two adjoining sections overlap, spaced about 18 inches apart, and then dead-ending each in opposite directions.

Yard sectionalization is easily arranged. On account of the slow movement of trains the wood section break can be used without movable approach. Tracks do not have to be sectionalized individually but can be grouped; ladder tracks, however, should always be kept separate. The sectionalization of yards is largely determined by the manner in which the switching is done, and for that reason the local conditions should be carefully studied in conjunction with the operating officials.

The various yard sections are supplied from a feeder through disconnecting switches, and if the yard is sufficiently large it is advisable to arrange the feeder in loop form, placing an automatic circuit breaker at each end of the loop. The feeder should again be subdivided into several sections by disconnecting switches.

Special Construction

This covers the work at cross-overs, river crossings, arrangements for joint use of the same overhead wire in yards and sidings by the 11,000 volt a-c. locomotives and the 600 volt d-c. trolleys at different times, grade crossings of 11,000 volts a.c. and 600 volts d-c., and many other problems which although of minor importance are links in the complete chain.

Cross-overs are all equipped with a single catenary, omitting the 4/0 copper wire. Wherever possible, air sectionalization is used but there are a number of places where wood section breaks could not be avoided. Perfect alignment is necessary where main line and cross-over catenaries meet, and at these

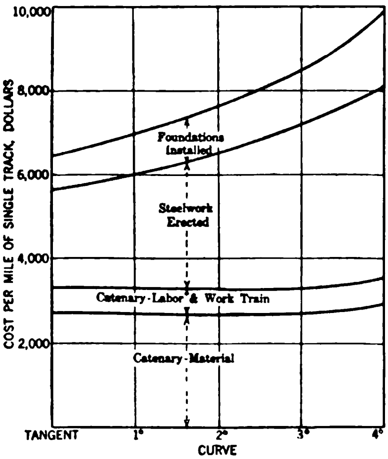


Fig. 10—Cost of Compound Catenary for Six-Track Section

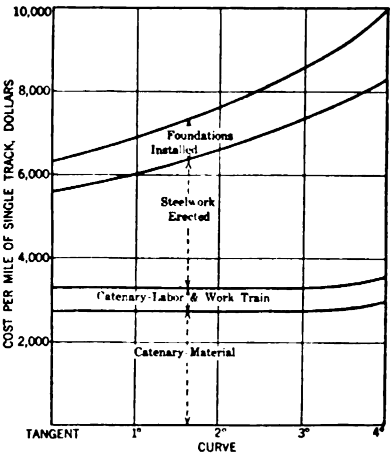


Fig. 11—Cost of Compound Catenary for Four-Track Section

points deflectors are used to prevent the pantagraph shoe catching in the wires.

The construction for river crossings presents unique studies. Of these crossings one is spanned by a drawbridge and the others by rolling lift bridges of various designs. On the lift bridges each pound of construction had to be compensated for in the counterweight, the total additional increase in weight being limited by the bridge foundations. The track, feeder and current-return circuits, three-phase transmission and signal lines, control and ground wires were carried across the rivers on high transmission towers; the United States Government specifying the minimum clearance between mean high water

and lowest point of wires over the channel, which varied between 135 ft. and 165 ft. Excepting at one place, where towers were placed in the river on both sides of the bridge, these high towers are combined with the anchor bridges which take the dead-ends of the main line catenaries (Fig. 9). A light contact system is carried between the towers.

Cost Data

It is of little value to give costs without at the same time stating fully the exact conditions under which they have been obtained. The diversity of conditions on the New Haven and its allied lines has clearly shown that the cost per mile of single track may vary considerably. The information in the following diagrams and tables is intended to give an idea of the cost of the various types of construction under "normal conditions" met within this territory, and also show how this may vary under more difficult conditions.

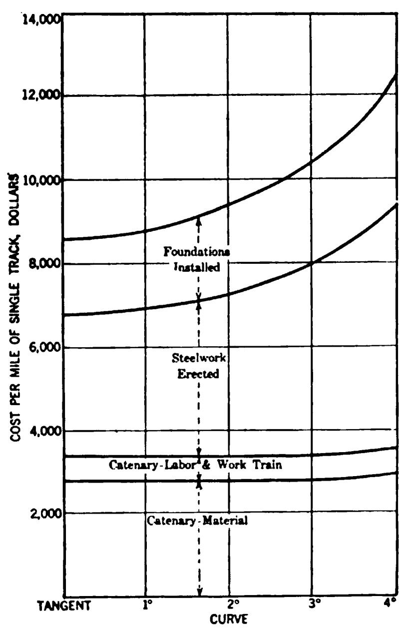


Fig. 12—Cost of Compound Catenary for Two-Track Section

Catenary Construction. Figs. No. 10, 11 and 12 give the respective cost per mile of single track for compound catenary construction of the New Haven type for a six-track, four-track and two-track section, exclusive of feeders, transmission lines and sectionalization.

Figs., No. 13 and 14 give the respective cost per mile of single track for single catenary construction of the New Haven type for four-track and two-track sections, exclusive of feeders, transmission lines and sectionalization.

These curves apply to the following normal conditions:

(1) *Foundations*. The ground on both sides of the tracks is level; no piling or rock blasting necessary.

(2) *Bridges*. To carry one catenary, one signal, one 4/0 feeder per track; duplicate 4/0 three-phase lines; duplicate

signal lines, each consisting of two No. 3 control wires and two $\frac{3}{8}$-inch steel ground wires. No bridge to span more than the standard number of tracks nor carry additional load, such as yard cross-spans, brackets, etc. None of the feeder supports to be moved in from the posts to the trusses.

(3) *Labor and Work train conditions for installation of Catenary.* Gangs and worktrains occupying tracks assigned for construction purposes to be allowed reasonable freedom from interruption.

Table 1 shows the different items which make up the total

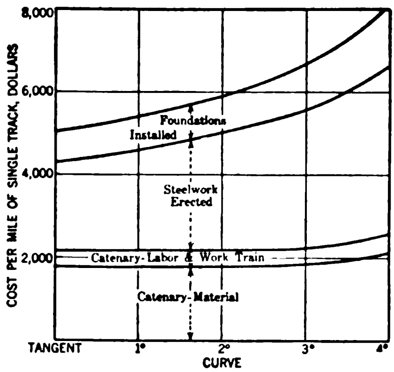


FIG. 13—COST OF SINGLE CATENARY FOR FOUR-TRACK SECTION

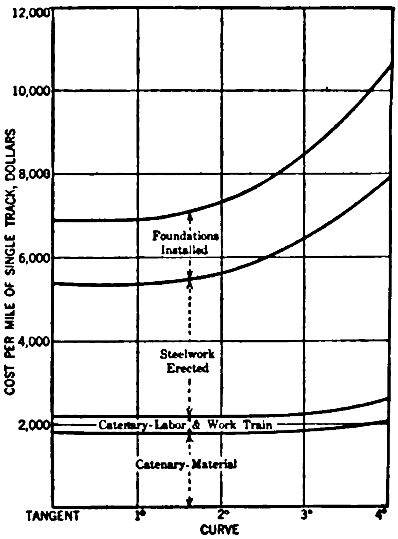


FIG. 14—COST OF SINGLE CATENARY FOR TWO-TRACK SECTION

labor and worktrain cost for catenary erection and the percent of each.

For items Nos. 2, 3, 4, 5, 6 and 9 the time paid is about twice the actual working time even under the above assumed "average conditions." The lost time is spent on sidings clearing for important trains and on the trips between headquarters and working points.

Item 7 is high due to the fact that much assorting and assembling of material was done at the storeroom.

(4) *Catenary Material.* Table 2 shows in per cent the different items making up the cost of catenary material. The

item of catenary material is not inclusive for special work, such as cross-overs, sidings, sectionalizing, nor does it include the dead-ends for the catenaries, which latter are included in the cost for sectionalizing.

Variation in Cost. Table 3 gives an idea of the increased cost when applied to difficult sections.

Sectionalization. The costs given in Table 4 apply to stand-

TABLE I.

LABOR AND WORKTRAIN FOR ERECTION OF CATENARY

Table giving distribution of labor and worktrain service in per cent

(1) Pulling out ⅜" strands	4.8 per cent*
(2) Locating saddles; spreading and sagging ⅜" strands	7.9 per cent*
(3) Putting up I beams with insulators attached	6.3 per cent.
(4) Pulling out ⅝" messenger; 4/0 copper and 4/0 steel wire	6.7 per cent†
(5) Clipping in	25.2 per cent
(6) Final adjustment	4.8 per cent
(7) Storeroom	18.9 per cent†
(8) Painting ⅜" messenger	13.3 per cent
(9) Painting ⅝" catenary (except 4/0 wires)	13.0 per cent
Total labor and worktrain for erecting compound catenary	100.0 per cent

*Can be omitted for single catenary.
†Can be partly omitted for single catenary.
Relation of compound to single catenary is 100 to 64.1

TABLE II.

CATENARY MATERIAL

Table giving distribution of material in per cent.

(1) ⅝" grounded steel messenger	26.2 per cent*
(2) Saddles complete	1.6 per cent*
(3) 3" I beams with fittings	7.4 per cent*
(4) Suspension insulators complete	8.2 per cent
(5) ⅜" messenger	15.7 per cent
(6) 4/0 copper wire	21.6 per cent
(7) 4/0 steel trolley wire	8.5 per cent
(8) ½" hangers complete	6.0 per cent
(9) Duplex clips between copper and steel wires	0.7 per cent
(10) Bolts, etc	4.1 per cent
Total for compound catenary, exclusive of dead ends	100.0 per cent

*Can be omitted for single catenary.
Relation of compound to single catenary is 100 to 64.8

ard sectionalizing bridges as used on the New Haven Road. (Costs for outdoor substations not included.)

Feeder and Transmission Lines. Costs for feeder and transmission lines have not been included in the tables, since these present no new features excepting such as arise from the conditions under which the wires were strung. The erection cost varies from $20.00 to $50.00 per mile of wire.

Yard Construction. In large yards of regular layout the total cost can be as low as $3000.00 per mile of single track, inclusive of sectionalization and feeders. In small yards with short tracks and irregular layout the cost will be necessarily increased. Much depends on the importance of the yard and the factor

TABLE III.

Table to show variation in total cost and cost of different parts, due to local conditions.

(1) Fairly regular layout; very few curves; some piling under foundations; sections of relatively new fill requiring large foundations.

(2) 25 per cent curves; restricted right-of-way for a considerable distance, making it necessary to move feeder supports in, thus increasing the stresses on the bridges; yard cross-spans attached to many bridges, some bridges spanning more than standard number of tracks.

(3) 32 per cent curves; some piling under foundations; fills requiring large foundations; cuts where rock blasting was necessary for the foundations; a number of bridges carrying yard cross-spans.

	Total cost per mile of single track of compound catenary, exclusive of sectionalization and feeders	Number of tracks	Cost of foundations in per cent	Cost of catenary bridges in per cent.	Cost of catenary constrn. in per cent.
1	$8,000.00	4	26 per cent	36 per cent	38 per cent
2	11,000.00	4	20 per cent	47 per cent	33 per cent
3	11,000.00	6	29 per cent	39.5 per cent	31.5 per cent

TABLE IV.

COST FOR STANDARD SECTIONALIZING BRIDGE

	Compound catenary.			Single catenary	
	6-Track	4-Track	2-Track	4-Track	2-Track
Foundations	$2,000.	1,720.	960.	960.	620.
Steel work	2,600.	1,760.	1,000	1,360.	720.
Electrical apparatus	11,500.	10,000.	7,000.	10,000.	7000.
Sectionalization	750.	500.	250.	500.	250.
Total	$16,850.	13,980.	9,210.	12,820.	8590.

of safety used. For favorable conditions the costs may be approximated as follows:

Foundations installed	$ 700.00
Supporting Structures erected	800.00
Catenary Material	1000.00
Labor & Worktrain Service	500.00
Total per mile of single track	$3000.00

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., July 1, 1915.

CONSTRUCTION, MAINTENANCE AND COST OF OVERHEAD CONTACT SYSTEMS

PART II—CATENARY CONSTRUCTION

BY F. ZOGBAUM

ABSTRACT OF PAPER

This paper is designed to give a general review of the problems involved in the maintenance and the cost of an overhead contact system of the catenary type, carrying high-voltage propulsion currents. The paper includes not only the contact system itself, but the transmission lines which form an integral part of the same. The subject treated is the catenary construction on the New York, Westchester & Boston Railway which is purely an electrical line, having no steam whatever. Several points will be brought out, such as the method of maintenance, the organization of the maintenance forces, the efficiency of insulation and other points which may be used in comparison and in discussion.

ONE OF THE most important matters pertaining to the maintenance of an overhead catenary system is the inspection of the contact wires and the transmission system, in order that possible failures may be forestalled, so that defects may be discovered and failures prevented. During such an inspection it is important always to note the condition of the contact wire with reference to its position to the track, and at all times to keep the wire as near the center of the track as possible.

Although on some other roads it has been found advisable to stagger the contact wire in order to get the maximum wear on pantagraph shoes, it will be seen from figures that are presented here, that it has not been found necessary in the case of this system to stagger the contact wire to the advantage of pantagraph shoe wear. In noting the position of the contact wire with reference to the track it is essential always to allow for the swaying movement of the locomotive or car carrying the pantagraph. This is especially important on curves, as trains running at high speed on curves of any sharpness over one degree, will naturally swing the pantagraph towards the outside of the

curve, making it necessary to have the contact wire outside of the center line of the track, whereas, on tangents the wire is kept as nearly as possible directly over the center of the track.

The line of the New York, Westchester & Boston Railway the catenary system of which is treated herein, consists of 54.26 miles of contact wire and 181.29 miles of transmission lines, which include signal feeders and control line, or 109.17 miles of transmission lines for traction power only. The 54.26 miles of contact wire is suspended over 30 per cent curve track and 70 per cent tangent track, so that practically the only adjustment necessary is on 30 per cent of the road, as the tangent contact wire remains in relatively the same position throughout the year, while the curve contact wire needs slight adjustments from time to time. Included in the catenary system are six sectionalizing or anchor bridges and 77 high-tension oil circuit breakers, which are used for sectionalizing the high-tension power. Also, it is considered on this line that the signal transmission lines are included in the electrical distribution or catenary system.

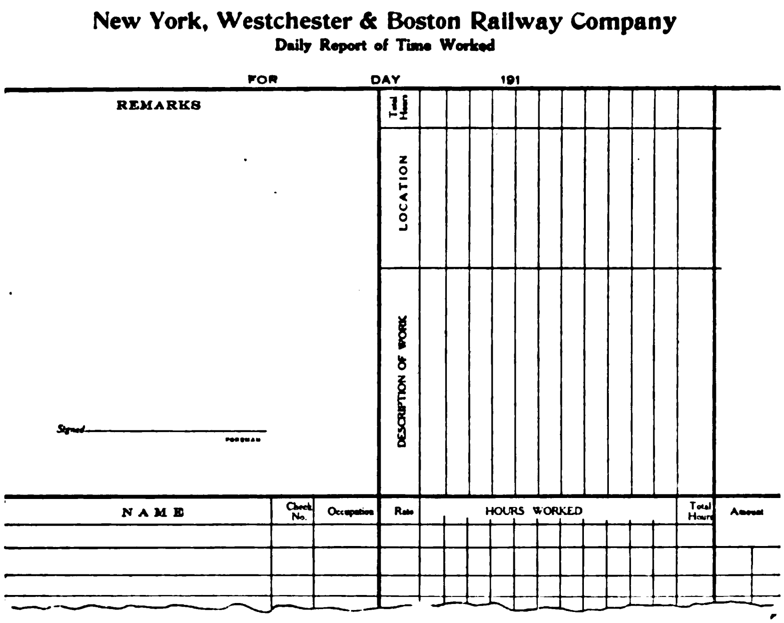
Organization

The organization for maintenance of the catenary and transmission system is known as the electrical department and includes, not only the maintenance of the contact system, transmission system, signal transmission system, signal transformers and station lighting, and elevator transformers, station elevators and lighting systems, but also takes care of such construction work as may come up from time to time. The electrical department is headed by the engineer of maintenance, to whom the general electrical foreman reports direct. The general electrical foreman has under him, one day foreman and one night foreman, five linemen and one assistant lineman. The day foreman, three linemen and assistant lineman cover the entire system, the majority of the time without special work train, and make repairs on practically all the apparatus as mentioned, except the contact system or parts of the transmission system, which cannot be taken out of service during the day. The night foreman and two linemen cover the entire line and use a work train in inspecting and repairing the contact system. The work train consists of one gasoline electric locomotive and work car. The gasoline locomotive contains

the working platform from which repairs are done to the contact system. Erected on the work car is a pantagraph collector, identical with those used on the regular coaches and locomotives. Also on the work car is an electric search light, which is used in inspection as well as when making repairs.

Inspection Methods

During the day time, approximately once each month, the contact system is given a general inspection from the head end



New York, Westchester & Boston Railway Company
Daily Report of Time Worked

FOR DAY 191

REMARKS

LOCATION

DESCRIPTION OF WORK

Signed
FOREMAN

NAME	Check No.	Occupation	Rate	HOURS WORKED	Total Hours	Amount

FIG. 1

of multiple-unit trains, and the pantagraph collector is watched during the entire run over the road and any defects or any wire off center are noted.

At specified times each month the circuit breakers on the sectionalizing bridges are inspected and repairs made if necessary. Any defects or other matters of irregular appearance are immediately reported and the night gang is lined up to make the stated repairs or adjustments.

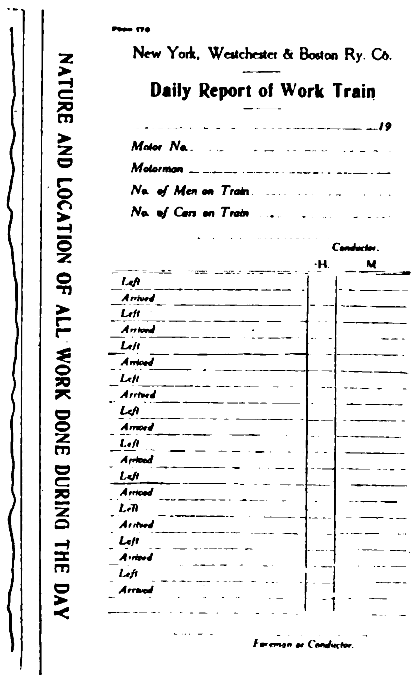
The night crew also makes specified inspections on the line repairing where necessary, but generally the entire time of

the night crew, which is actually only about $4\frac{1}{2}$ to 5 hours, due to traffic conditions, is taken up with regular maintenance work, which has been previously lined up for it.

The day crew reports its work on a regular form, as shown in Fig. 1, and the night crew also uses the same form, and in addition, turns in a work train report, as shown in Fig. 2, which includes the movement of the work train, as well as specifying what work has been done and what the general condition of the line is in when the crew returns from the road.

Results of Inspection

As already stated, a constant inspection has rapidly reduced the slight difficulties which arose from time to time after the road was first put into operation.


NATURE AND LOCATION OF ALL WORK DONE DURING THE DAY

New York, Westchester & Boston Ry. Co.

Daily Report of Work Train

19

Motor No.

Motorman

No. of Men on Train

No. of Cars on Train

Conductor.

H. M

Left

Arrived

Left

Arrived

Left

Arrived

Left

Arrived

Left

Arrived

Left

Arrived

Left

Arrived

Left

Arrived

Left

Arrived

Left

Arrived

Foreman or Conductor.

Fig. 2

For example: For the year ending December 1913, a total of 37 pantagraph collectors were broken, out of 91,250 pantagraph trips made during the year. For the year ending December 1914, there were 19 pantagraph collectors broken out of 94,900 pantagraph trips made during the year; and for the three months ending March 1915, four pantagraph collectors were broken out of 23,400 pantagraph trips made during the three months; making 2,466 pantagraph trips, per one pantagraph failure in 1913; 4,994 pantagraph trips, per one pantagraph failure in 1914; and 5,850 pantagraph trips, per one pantagraph failure for the three months ending March 1915.

Operating Efficiency

In 1913 there were 27,927 car miles operated per one pantagraph failure, in 1914 there were 55,503 car miles operated per one pantagraph failure, and for the three months ending March 1915, there were 64,799 car miles operated per one pantagraph failure.

The usual cause for broken pantagraphs is due to wire off center, low joints on running rails on curves, overhead frog on deflector out of adjustment and loose sleeves on contact wire.

The following tables give the total delays caused by broken pantagraph collectors and power troubles, shown in comparison with the train miles operated, with the typical causes given for the delays.

Year	Month	Train miles	Power trouble		Pantagraph and contact wire trouble	
			Delays	Minutes	Delays	Minutes
1913	Jany.	73939.07	29	584	1	5
"	Feby.	68,323.64	13	79	1	20
"	March	74,206.19	1	6	0	0
"	April	71,684.33	38	243	1	15
"	May	74,103.24	25	382	1	5
"	June	72,925.33	13	114	6	40
"	July	75,033.20	29	187	2	22
"	August	74,674.88	14	101	1	5
"	Sept.	72,223.94	9	92	1	10
"	October	74,644.30	9	62	1	7
"	Nov.	72,160.28	15	242	0	0
"	Dec.	75,386.58	15	78	0	0
		879,304.98	210	2170	17	129

Year	Month	Train miles	Power trouble		Pantagraph and contact wire trouble	
			Delays	Minutes	Delays	Minutes
1914	Jany.	75,330.00	16	227	4	25
"	Feby.	67,088.08	20	398	1	5
"	March	74,634.69	2	2	0	0
"	April	71,044.61	1	5	0	0
"	May	74,160.23	8	434	1	7
"	June	72,312.00	8	33	4	51
"	July	75,387.60	3	14	0	0
"	August	74,406.68	19	927	0	0
"	Sept.	72,241.02	0	0	0	0
"	October	74,659.04	0	0	0	0
"	Nov.	72,216.96	9	109	2	12
"	Dec.	74,639.48	11	107	3	17
		878,120.39	97	2256	15	117
1915	Jany.	74,627.36	0	0	0	0
"	Feby.	67,388.36	0	0	1	2
"	March	74,654.61	0	0	0	0
		216,670.33	0	0	1	2

TYPICAL CAUSES FOR DELAYS CAUSED BY:

	Power Troubles		Contact Wire and Pantagraph Trouble
		1913	
Jan. 2nd:	Power off three minutes, due to undiscovered grounds	Jan. 4th:	Contact dead end broken by pantagraph
		Jan. 4th:	Grounds due to broken pantagraph
Jan. 9th:	Power off three contact lines, four minutes, due to undiscovered grounds	Jan. 17th:	Short circuit of pantagraph insulator, due to foreign material
		Jan. 21 :	Short circuit of pantagraph insulator, due to limb of tree.
February		Feb. 10 :	[illegible] messenger grounding against lower cord of highway bridge.
		Feb. 14 :	Broken pantagraph on cross-over, on account of deflector.
March		March 5th:	Broken pantagraph, due to train running past deadend in storage yard.
		March 11 :	Due to car in storage yard bridging current on line to ground, by raising two pantagraphs.
		March 15 :	Broken pantagraph, due to pantagraph sprocket chain breaking.
May		May 2nd:	Grounded insulator on contact wire.
		May 24th:	Short circuit on pantagraph insulator, due to foreign material.
		May 25th:	Broken pantagraph on curve, due to loose hangers.
		May 25th:	Pantagraph broken on cross over, due to deflector.
		May 29th:	Short circuit on pantagraph insulator, due to cat on roof of car in storage yard.
July		July 7th:	Broken sprocket chain on pantagraph on cross-over, due to deflector.
		July 13 :	Short circuit of pantagraph insulator, due to limb of tree.
		July 14 :	Broken sprocket chain on pantagraph on cross-over, due to deflector.
		July 20 :	Broken pantagraph on cross-over, due to deflector.
		July 25 :	Broken pantagraph on cross-over, due to deflector.

Power Troubles		Contact Wire and Pantagraph Trouble	
	1914		
Feb. 16 :	Power off five contact lines, five minutes, due to undiscovered grounds.	Feb. 17 :	Grounded line switch on car
		Feb. 18 :	Due to grounded transformer on car.
March 1:	Grounded feeders, due to protection screens being broken down by snow.	March 20 :	Grounded contact wires, due to ice connecting between contact wire and highway bridge.
May		May	2nd: Grounded insulator on contact wire.
		May 6th:	Arc drawn by pantagraph grounding on messenger.
		May 18 :	Broken pantagraphs on two cars at cross-over, due to deflector.
		May 20 :	Due to arc drawn by pantagraph grounding on catenary bridge.
		May 27 :	Broken pantagraph, due to pantagraph leaving wire on curve.
		May 28 :	Grounded pantagraph insulator due to branch of tree.
August		Aug. 3rd:	Broken pantagraph breaking insulator on curve.
		Aug. 23 :	Due to grounded pantagraph, caused by bird on roof of car.
		Aug. 29 :	Broken insulator on contact wire.
	1915		
February		Feb. 3rd :	Due to arc drawn by panta graph, grounding messenger.

Also, the graphical chart shown under Figs. 3, represents the total minutes delay, divided between power trouble and contact wire and pantagraph trouble.

Insulation

All told, on the 54.26 miles of road, there are the following number of insulators:

On the 11,000-volt lines, there are 2,557 pin insulators, 1,949 safety strain insulators, 164 wood strain insulators, 2,004 catenary suspension insulators and 87 dead-end strain insulators; on the 2200 volt signal lines there are 1,368 pin insulators and 971 safety strain insulators; making a total of 9,100 insulators.

Out of the total number of 2,339 insulators carrying the signal

transmission lines there have been no insulator failures after approximately three years operation, and out of the 6,761 insulators carrying the 11,000-volt lines there have been the following failures:

In 1913: One insulator failure on contact lines

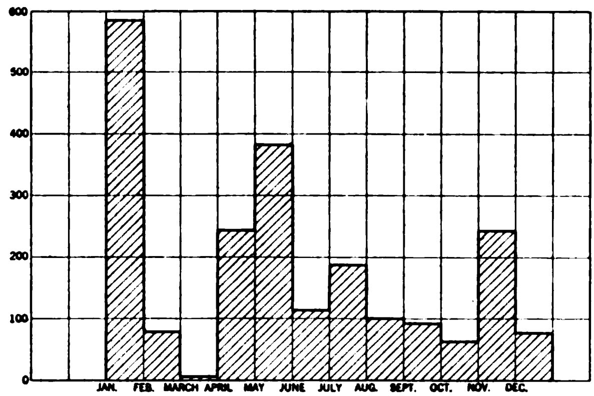


FIG. 3A—TOTAL MINUTES DELAY DUE TO POWER TROUBLE, 1913

FIG. 3B—TOTAL MINUTES DELAY DUE TO POWER TROUBLE, 1914

In 1914: Seven insulator failures, six of which were on contact lines and one on the transmission line

In 1915: There has been one insulator failure on the transmission lines.

This makes approximately 100 per cent insulation in 1913, a little better than 99 per cent insulation in 1914 and approximately 100 per cent so far in 1915.

Wear

The following table shows the mileage obtained by pantagraph shoes and it is to be noted also, that the actual wear on the contact wire from the rubbing effect of the shoe has amounted

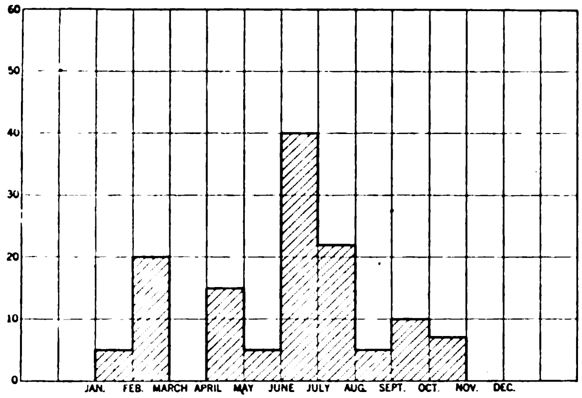


FIG. 3C—TOTAL MINUTES DELAY DUE TO PANTAGRAPH AND CONTACT WIRE TROUBLE, 1913

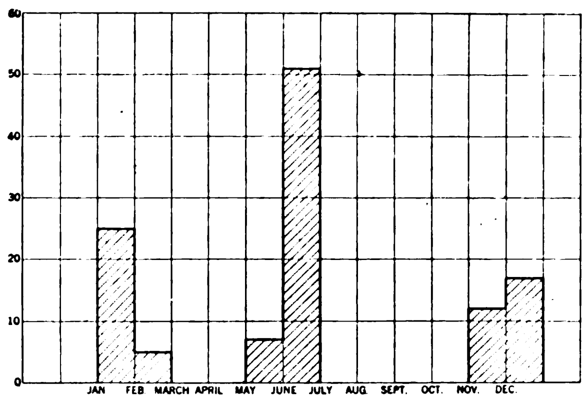


FIG. 3D—TOTAL MINUTES DELAY DUE TO PANTAGRAPH AND CONTACT WIRE TROUBLE, 1914

to about $\frac{1}{8}$ in flat surface on the under side of the grooved steel contact wire. This wear has been uniform over the entire line and there seems to be no indication of more wear on the low wire than on the high wire, and the wear on curves, also, is about the same, so that at the rate of wear as noted at the present

time, it should be not necessary to renew the steel trolley wire for six or seven years, at least, from the initial installation.

Year	Month	Pantagraphs broken	Mileage
1913	January	2	840
"	February	5	1049
"	March	3	1046
"	April	6	1109
"	May	2	1320
"	June	6	1357
"	July	5	1425
"	August	6	1866
"	September	0	2379
"	October	0	2667
"	November	1	1775
"	December	1	1669
		37	

Year	Month	Pantagraphs broken	Mileage
1914	January	4	1330
"	February	1	1144
"	March	0	1053
"	April	0	1333
"	May	3	1470
"	June	2	1885
"	July	2	2098
"	August	2	2127
"	September	1	2036
"	October	0	1541
"	November	2	1224
"	December	2	1145
		19	
1915	January	1	1210
"	February	1	1197
"	March	2	1091
		4	

It is to be noted in the above table that the mileage obtained by pantagraph shoes decreases in the winter months and increases in the summer months. This is due to the fact that it is necessary to raise the tension on the upward motion of the pantagraph in the cold weather, on account of the slight raising in the contact wire, caused by contraction.

Rules and Regulations

A book of rules has been issued for the instruction and guidance of employes in the electrical department, as well as the other departments. Particular importance is laid on rules of safety and it is made clear to all the men engaged in high tension work, that great care must be taken to avoid coming in contact with any electrical equipment. The men are carefully examined in all the rules, as well as to their knowledge of general high-tension work. The following are some of the rules which the men are required to obey under penalty of dismissal:

All high-tension feeders, catenary wires, busses, oil switches and other high-tension apparatus, shall be considered alive at all times and shall be considered dead only when specified by the proper authority.

Employes whose duties require them to work in the vicinity of or in direct connection with, any high-tension apparatus, trolley wires, feeders or busses, are cautioned against the dangers involved and are forbidden to engage in such work unless duly authorized and properly protected.

No attempt shall be made to work on any of the 11,000-volt system, namely, feeders, trolley wires, anchor bridge apparatus, bomb fuses, lightning transformers and high-tension telephone lines, while it is alive.

If at any time there is doubt about the condition of any piece of 11,000 volt apparatus, no work is to be attempted. In case of feeders or trolley wires, which are always to be *considered* alive, no work is to be attempted until they are properly "grounded" in the immediate vicinity of point where men are to work.

A proper ground will be established by connecting, by means of a clamp, one end of a piece of *stranded* copper cable, not less than No. 0000 in size, to any iron work *known* to be connected to the running rails of the railroad and the other end connected to the feeder or trolley wire by a second clamp, this clamp to be operated by means of a pole at a distance of not less than six feet (6′) from *below* the feeder or trolley. The "ground" end of the wire must be applied first while grounding a feeder or trolley, and removed last while clearing or removing ground from feeder or trolley.

No 11,000-volt switch will be operated except by means of dry wood poles provided for the purpose. Operator's hands must never be placed at a distance less than six feet from live end of pole.

No work shall be attempted on any 11,000-volt automatic circuit breaker or 11,000-volt transformers, without first disconnecting it from power supply, by means of disconnecting switches provided with the apparatus.

No work shall be attempted on one or more transformers which are connected together for three phase operation without first disconnecting all transformers of the group from power supply by means of disconnecting switches provided for the purpose.

No unauthorized person shall be allowed in the vicinity of unprotected apparatus or allowed to assist workmen engaged on 11,000-volt apparatus.

Also, the following instructions are issued to all employees of the road, so that they may be properly guided and instructed with reference to the electrical equipment.

All employes, except those who are properly authorized, are forbidden to enter upon or climb any catenary bridge or pole, signal or anchor bridge.

All employes, except those who are properly authorized, are forbidden to go within six feet of any high-tension apparatus, feeders or busses.

All employes of this Company, except those who are properly authorized, are forbidden to climb upon the roof or superstructure of any car, locomotive or other equipment.

As the entire handling of the power on the line is done by one set of men, namely, the load despatchers, who have entire jurisdiction over the cutting in and cutting out of the various high-tension lines, a special set of instructions have been issued for this purpose. These instructions cover the method of opening and closing high-tension circuit breakers, etc. Portions of these instructions are shown below.

Instructions to Load Despatchers

If, for any reason, a track wire is desired cut out, Load Despatcher will first take up the matter with the Train Despatcher and get his O. K. by a written message transmitted by telephone before the track wire is cut out, in order that there will be no power shut off while a train is in this section.

If a ground occurs on the line, Load Despatcher will immediately get in touch with Train Despatcher advising him just what tracks are out, and if possible, in what particular section ground occurred. Train Despatcher will get in touch with all trains in this section and advise Load Despatcher if any train in the said section has caused ground. Load Despatcher, upon receiving information from Train Despatcher that he has no train in this section which reports ground, will throw power on line a second time. If power fails to hold on second trial, Load Despatcher will not throw power on again until definite information is received from some definite source, either through Train Despatcher or representative of the Maintenance Department, that line is clear; this information must be sent in the form of a phonogram. If a ground occurs on any track or feeder causing circuit breaker to open, a period of at least five minutes must elapse before power is cut in, on said track or feeder, unless positive information is received as to the cause of interruption.

Orders to Towermen, Anchor Bridge Operators and Signal Maintainers, instructing that circuit breakers or switches be opened or closed, must

be done by a written order stating specifically what this operation is to be. The men instructed to carry out the orders will reply when same is complete by written message.

If any circuit breakers open automatically on a ground or for any other reason, the Towerman at the point where the circuit breaker has opened will inform the Load Despatcher which breaker opened.

When any men are working on the line that has been cut out, power

FORM 179

NEW YORK, WESTCHESTER & BOSTON RAILWAY CO.

FAILURE REPORT CATENARY SYSTEM DATE 191

POWER OFF			DESCRIPTION OF FAILURE	Train No.	Detention to Train if any	LOCATION	CAUSE OF FAILURE
From	To	Time Elapsed					

FIG. 4

is not to be thrown back until the foreman in charge of the line gang has reported by written message to the Load Despatcher that his men are entirely clear and all grounds have been removed from the line and Train Despatcher notified.

If at any time pantagraphs are broken on any of the trains and the trouble has not been ascertained, no train should be run through this

Form 281 New York, Westchester & Boston Ry. Co.

POWER ORDERS

Maintenance Dept. Date 191

SYMBOL	LOCATION	Message sent to Cut out	O. K'd by Load Desp.	Message Sent by	Message sent to Cut in	Message Sent by
		M.			M.	
		M.	M.		M.	
		M.	M.		M.	
		M.	M.		M.	
		M.	M.		M.	
		M.	M.		M.	
		M.	M.		M.	

Foreman

FIG. 5

section until the trouble has been ascertained, and it is found safe to run trains by the point where the pantagraph was broken.

INSTRUCTIONS TO TOWERMEN IN OPERATING SWITCHBOARDS CONTROLLING HIGH-TENSION POWER

No circuit breakers or switches shall be closed without written orders from the Load Despatcher.

If any circuit breaker opens automatically on a ground, overload

MAINTENANCE ELECTRICAL COSTS.

Description	October 1912	July 1914	Aug. 1914	Sept. 1914	Oct. 1914	Nov. 1914	Dec. 1914	Total for 6 months	Average per mo. for 6 months
Feeders..................	$ 19.31	58.51	257.95	98.06	94.82	8.67	29.40	547.41	91.23
Contact..................	955.25	163.19	144.45	176.81	162.14	204.95	245.27	1096.81	182.80
Miscl. Elec. Expr...........	291.81	790.15	706.92	753.77	837.27	985.48	777.46	4851.05	808.50
Supervision................	240.00	384.87	399.24	394.17	372.66	360.79	263.49	2175.22	362.53
Totals................	$1506.37	1396.72	1508.56	1422.81	1466.89	1559.89	1315.62	8670.49	1445.06

Description	October 1912		Last Six Months	
	Feeders	Contact	Feeders	Contact
Total Maint. incl. Supervision & Miscl. Elec. Expenses..................	24.12	1482.25	489.38	955.68
" " not" " " " " "	19.31	955.25	91.23	182.80
" " per mile single track, incl. Supvr. & Miscl. Elec. Exp. 54.26 mi..........	0.44	27.31	9.01	17.61
" " " " " " not inlc. Supvr. 54.26..................	0.35	17.60	1.68	3.36
" " " " of feeders, incl. Supvr. & Miscl. Elec. Exp. 181.39 mi..........	0.13		2.69	
" " " " of contact, incl. Supvr. & Miscl. Elec. Exp. 54.26 mi..........		27.31		17.61

or for any other reason, he must immediately get in communication by telephone with Load Despatcher, and inform him in detail what has taken place. It is especially important to note when any circuit breaker opens it is not to be closed again without an order from Load Despatcher.

MAINTENANCE RECORDS AND COSTS

A record is kept of all the failures on the electrical system and is shown each day on a blank filled out by the load despatcher and checked by the maintenance forces, and is shown in Fig. 4.

Records are also kept of all lines worked on by the electrical forces showing just what lines were taken out of service. This report is filled in on a blank, as shown in Fig. 5.

The following table shows the various costs of maintenance of the overhead contact system, and for a matter of comparison the figures are shown for October 1912, shortly after the system was put into operation, and an average for the last six months ending December 1914. Included in the cost per unit is the cost of miscellaneous electric line expenses, which includes sectionalizing bridges, sectionalizing equipment, time of men while on emergency duty, work train, and in fact, all charges which cannot be placed actually against feeders and contact.

For a matter of comparison, the cost of electrical maintenance is given per car mile for July 1914 and December 1914, as follows:

Total Maintenance per car mile, July 1914......$ .0156
Total Maintenance per car mile, December 1914 $ .0142

The above figures include supervision, transmission and contact system, miscellaneous electric line expenses, work train, etc.

It will be seen in reviewing the above paragraphs that the various difficulties, none of which were serious, and the costs involved in overcoming the same, have decreased as time progresses, and we would, therefore, assume that the inverted peak of the triangle has not as yet been reached.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., July 1, 1915.

TOP CONTACT UNPROTECTED CONDUCTOR RAIL FOR 600 VOLT TRACTION SYSTEMS

BY CHARLES H. JONES

ABSTRACT OF PAPER

The paper treats with the various factors which enter into consideration in the design of a 600 volt contact rail system.

The weight of rail to be used depend upon conditions met with in each case, but in general, a heavy rail is preferable from all points of view.

The question of quality is rather indeterminate, but in general, it is not advisable to use soft steel until the weight has been brought up to at least 80 lb. (36.28 kg.) per yard, however, consideration should be given to it above this weight.

Insulating and supporting is a mechanical problem which must be decided upon local conditions.

The method of bonding and jointing to be used depends upon size and section of rail used. With A. S. C. E. standard, the foot bond is the most satisfactory, above this weight and with special sections of rail a copper welded joint will be very satisfactory.

Provisions must be made to control the expansion and contraction of rail by cutting it into sections and anchoring each of these sections. Various methods of connecting rails are described together with special devices which will be required.

The costs of constructing a single track mile of contact rail uisng 50 lb. (22.68 kg.) rail is $3,284.29 while the cost of the same amount of 80 lb. (36.28 kg.) rail is $4,028.55. The average maintenance cost per mile of rail, exclusive of entire renewal, is $80.00 per mile per year.

THIS PAPER will deal with the various factors which enter into the construction, operation and maintenance of a top contact, unprotected third rail located to one side and above the gage line of the track rail, on a heavy 600-volt direct-current traction system using a gravity type collecting device such as that shown in Fig. 1.

The following elements enter into, and should be given consideration, in the laying out of such a system: Weight of rail; quality of rail; insulating and supporting; bonding and jointing; anchoring; special work required; method of connecting at crossings; cost of installation and maintenance.

Weight of Rail. Rail weighing from 40 lb. (18.14 kg.) to 150 lb. (68.04 kg.) per yard has been used for this purpose. The

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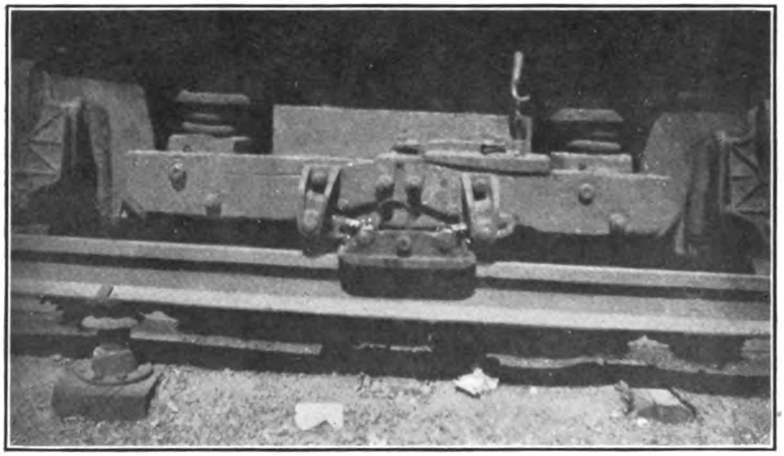
lighter weights of rail, 3 lb. (18.14 kg.) to 50 lb. (22.68 kg.) were used almost exclusively on the oldest installations of this type of contact system and have been in service about 20 years. This light weight rail is not as satisfactory as a heavy one, and in recent years has been practically abandoned for a heavier rail, except for yard purposes where it can still be used to good advantage, since high conductivity is not required, and its life in this class of service will be very long. In some instances a T iron with its flat surface turned up has been used for contact rail in yards to good advantage. For main line purposes the lighter rail requires closer maintenance, since it lacks the necessary rigidity, its light weight will limit its life, while the installation cost will almost equal that for a heavy rail. The later installations of contact rail systems have used rail varying from 80 lb. (36.29 kg.) to 150 lb. (68.04 kg.) per yard, the larger size being used on extremely heavy traction systems. The great advantage to be gained by the use of heavy rail lies in the fact that a large amount of conductivity can be installed for almost the same amount of labor charge as that required to install a lighter rail, serving as a contact member only, which will necessarily have to be backed up by a paralleling feeder system, thus entailing a large auxiliary charge for a feeder system, such as cost of pole or duct line, etc. If a paralleling feeder system is required, even with an extremely heavy rail, the greatest advantage of heavy rail will be lost and a medium weight of rail, 80 lb. (36.28 kg.) to 100 lb. (45.35 kg.) will give more satisfactory results.

The question of rail section is closely related to the matter of the weight of rail to be used and is dependent to a great extent upon the gage of contact rail. For weight of rail up to and including 80 lb., A. S. C. E. section is a very satisfactory one to use providing conditions permit it. The distribution of metal is such that it can be easily supported, it is very rigid and is easily bonded and jointed. For a heavier rail it will be well to consider the advisability of using a special section which will throw more metal into the contact surface and thereby increase the life. The question of supporting this weight of rail is not as serious as with a lighter rail which is more easily distorted. On one system having 40-lb. (18.14 kg.) rail that was installed in 1897 there is about two years of useful life remaining, on another having 48-lb. and 50-lb. rail which was installed in 1895 there is about six or seven years of useful life. Another line having 80-

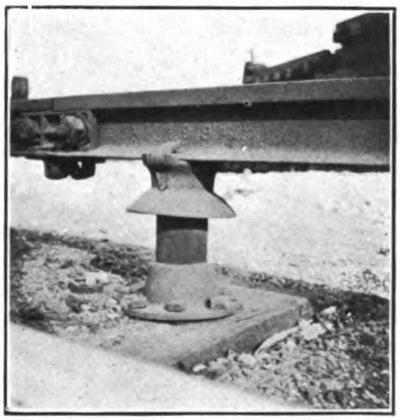


[JONES]

FIG. 1

[JONES]

FIG. 2



[JONES]

FIG. 3

lb. (36.28 kg.) rail which was installed twelve years ago shows a very small amount of wear up to date. These figures will give some idea of the life that can be expected. The length of rail may vary from 30 ft. (9.14 m.) to 60 ft. (18.28 m.) and should be determined somewhat by the weight. A light rail up to and including 80 lb. (36.28 kg.) may be satisfactorily handled in 60-ft. (18.28 m.) lengths, thus reducing the amount of bonding. For renewal or small repairs on this weight of rail 30-ft. (9.14 m.) lengths will be more easily handled and should be used although it will be necessary to sacrifice the gain in bonding. For rail above 80 lb. (36.28 kg.) in weight, 60-ft. (18.28 m.) lengths will be rather difficult to handle and better results can probably be obtained with 30-ft. (9.14 m.) lengths.

Quality of Rail. The conductivity of the rail will vary inversely with the percentage of carbon or manganese allowed to remain in the finished rail. The ordinary run of Bessemer rail will have a conductivity of about one-tenth that of copper, while a rail with a low percentage of carbon will have a conductivity one-eighth that of copper or an increase of about 25 per cent in conductivity. The price will increase from 18 per cent to 20 per cent on this quality of rail. Increasing the conductivity will make the rail considerably softer, thus requiring more careful handling to prevent it from being kinked during installation. It is very difficult to remove any kinks that may get in it, therefore the alignment may be affected. There is no appreciable difference in the rate of wear between the low carbon and ordinary steel in the class of service referred to in this paper. Whether or not it is advisable to use soft steel for contact rail is a question that must be decided for each individual location and for which no hard and fast rule can be set down. If it is contemplated to use a rail weighing less than 80 lb. (36.28 kg.) there is nothing to be gained, since increased conductivity can be gained by using a heavier weight of rail at a slight increase in cost and a greater increase in the advantage of a heavy rail. Above 80-lb. (36.28 kg.) rail the question requires careful consideration, since the gain in conductivity will cost almost as much as equivalent conductivity obtained by adding to the copper in the feeding system paralleling the rail. If by using the possible gain in conductivity with soft rail the expense of a pralleling feeder system can be eliminated, it will be worth while and should be done since it will eliminate the cost of providing a pole line or duct system for such feeders. On the other hand

there is a certain amount of intangible gain to be obtained by having a parallel feeding system, especially with the narrow working margin that is assumed when the difference in conductivity or rail would decide the question of whether or not a paralleling feeder system would be required.

Insulating and Supporting. The insulating of contact rail for a 600-volt system is more of a mechanical than an electrical problem and the type of insulator to be used depends upon local conditions, such as the clearance between bottom of contact rail and the ground, or whether on the surface or on an elevated structure. Impregnated wood, porcelain, reconstructed granite and composition insulation have been used with varying results depending upon the local conditions. Wherever there is any vibration, porcelain and reconstructed granite or insulators having any castings bolted together have not been satisfactory. In general, an insulator should be so designed that it will have a large leakage surface, so as to prevent current leaking across and causing burning during wet weather. It should hold the rail from moving sideways, but should allow lateral motion during expansion and contraction, otherwise it would be tipped or broken with rail movement. It should have a large bearing surface with provision for fastening to the tie with heavy lag screws which will not rust out quickly. Fig. 2, shows a type of impregnated wood insulator which has been satisfactory for various sizes of rail from 40 lb. (18.14 kg.) to 80 lb. (36.28 kg.). The base casting is the same size for all weights of rail, and the length of block and size of top casting are varied for the different weights of rail. The spacing of insulators will vary somewhat with the weight of the rail, but in no case should this be more than 10 ft., since a certain amount of deflection will occur and cause the rail to wear in spots. With 80-lb. (36.28 kg.) rail on straight track, insulators placed about 7 ft. (2.133 m.) apart on tangent track and 5 ft. (1.524 m.) on curved track give good results. The life of an insulator is from 10 to 12 years under ordinary conditions, although on one system a great many impregnated wood insulators have lasted from 15 to 20 years.

Bonding and Jointing. In order to provide for carrying current across joints in the rail it is necessary to provide a low resistance path, since a joint plate does not give good electrical contact. This is done by placing a copper bond or bonds of capacity equal to that of the solid rail around each joint. This

may be done in several ways, each of which have their respective advantages and disadvantages. A concealed bond with either a pin or pressed terminal under the plate is well protected, but cannot be readily inspected and if it does fail and start to burn in the terminal the hole is usually burned so badly that a new bond cannot be put in the same place, therefore requiring a different type of bond for replacement. A long bond with pressed or pin terminal applied outside of plate is easily inspected, but the cost is very great and mechanical protection is poor. A short bond which may be soldered or welded to the base or ball of the rail is cheap and easily inspected, but is very difficult and expensive to renew in kind under traffic. On an installation now under construction a cast copper weld is being made at the joints, in the extremely heavy rail that is being used, which will serve the double purpose of both bond and joint plate. This would seem to be a very satisfactory method to use on a very heavy special section of rail which would be hard to bond and joint in a satisfactory method by any other means. On one system a copper plate with an iron protection plate was riveted to the base of the rail thus serving the purpose of both bond and joint plate, but this is expensive to install and renew in kind. On standard rail section a very satisfactory method of bonding is to use a foot bond applied to the underside of the base of the rail with a hydraulic compressor, providing there are no mechanical interferences, such as wooden guard rails, lack of clearance to ground, etc. This bond is about as small as is possible to make a bond. It is easily applied, inspected, is well protected from mechanical injury and can always be replaced in kind. Bonds of greater capacity than 500,000 cir. mils should not be installed in any but the welded type, due to the difficulty in obtaining sufficient contact surface. If larger capacity is required it should be divided between two smaller bonds.

For jointing the rail, both two- and four-bolt plates have been used and from the results obtained it is thought advisable to use a four-bolt plate for all sizes of rail, since it holds the rail more firmly, requires less inspection and eliminates the possibility of having the bolt pulled out of the end of plate as sometimes occurs with a two-bolt plate on account of heavy strain due to contraction of rail. It will also help out the bonding due to holding the joint stiffer and preventing slight motion of the bond which has a great deal to do with the breaking of

bonds. Where foot bonds are used it will usually be necessary to notch out the bottom of the plate to allow clearance for the expanded bond terminal. Keeping the joints tight will do more toward maintaining contact rail in good condition than any other maintenance operation.

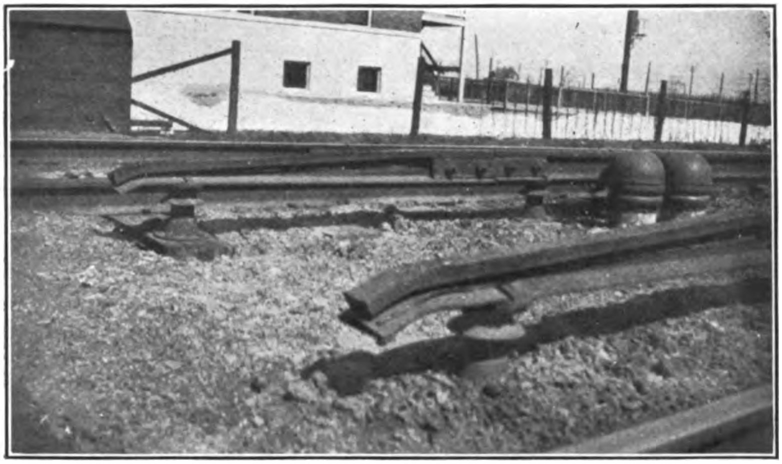
Anchoring. Due to changes of temperature the length of the rail will vary and to control the variation in length it is necessary to provide some means to force this expansion to take place along proper lines. This is done by cutting the rail up into lengths of from 1000 to 1200 ft. and anchoring it in the center of these stretches so that when it expands and contracts it will take effect in predetermined locations. The method of anchoring will depend on local conditions. On surface track that is not provided with a wooden guard rail the rail may be anchored by attaching several strain insulators of a substantial strength in multiple to an iron plate which in turn will be extended over and be bolted to several ties, the other end of these insulators to be fastened to the base of the contact rail. If a wooden guard rail is used an anchor block consisting of a piece of 6-in. by 8-in. oak 2 ft. long impregnated with a wood preservative may be attached to this guard rail and the contact rail in turn is bolted to this block. If it is thought advisable, a set of porcelain insulators may be placed between this block and the guard rail. These openings between stretches of rail, commonly called expansion gaps, may be made in several ways. One of these is to use a plate with a slot in one end instead of a hole, using long bonds with a loop of slack in them to take care of the change in length. This is not very satisfactory on account of the ends of the rail wearing very rapidly at this joint, and pounding is soon caused by trolley collectors. Another method is to cut and fit two adjacent ends of rail as shown in Fig. 3, connecting a long bond around the joint. This will give a good running surface and will take care of considerable expansion. The best method of providing the expansion gap is to end each run of rail with a suitable incline leaving a three foot space between each stretch of rail. In a good many cases, especially on surface track, it will not be necessary to have an opening in the contact rail, due to street crossings, special work at cross-overs, etc., which will take the place of this expansion gap. Fig. 4, shows a good method of anchoring short lengths of rail, using a wood strain insulator.

[JONES]

FIG. 4

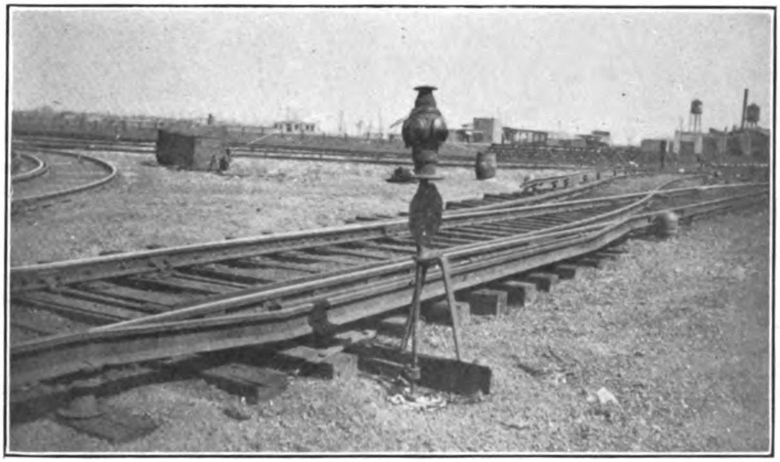
[JONES]

FIG. 6



[JONES]

FIG. 5



[JONES]

FIG. 7

[JONES]

FIG. 8

Special Work Required. Several kinds of special devices are necessary to pick up collecting devices (otherwise called trolley shoes) from their free position to the elevation of the contact rail. The most common of these is the end incline (Fig. 5). This is made from a piece of steel rail having the web cut out and the ball bent down to meet the base and a countersunk head rivet driven in the end to keep the two parts together. This incline should have an angle just sufficient to pick up a shoe without causing it to jump, and on the other hand the incline should not be any longer than necessary otherwise a heavy arc will be drawn at the trailing incline when a car leaves the end of the rail before it makes contact on the next stretch of rail. In some instances a very sharp angle incline has been used on the trailing end of a rail, but this is not satisfactory, since at any time it might be necessary to reverse traffic on a stretch of track and then the incline would be too short, causing shoes to jump, thus burning the rail or possibly breaking the shoe on the car. At cross-overs where it is necessary to open the main contact rail and not leave a space without contact rail, greater than the distance from center to center of car trucks, it is necessary to place a piece of short rail that is set on the opposite side of the track starting at a point just back of the heel of the switch and extending to a point opposite the continuation of the main rail, which is just beyond the track frog on the track in question so that a trolley shoe on a car going through the cross-over will not strike the main rail. This rail is called a lap rail and in general is less than 100 ft. in length. A good method of providing inclines on this rail is to have the incline formed on the end of a full length of rail. Where a contact rail is normally placed on the outside of two adjacent tracks and a cross-over is located it is not necessary to have a lap rail, but some means must be provided for raising the trolley shoe of a car going through the cross-over up onto the approaching rail from the side. This may be done by one of two methods. One is to provide a side incline approach (Fig. 6), which is nothing more than a straight switchpoint with a standard end incline formed on the end. This device is attached to the side of a main contact rail with the thin end of the point opposite the switch point in the track. The angle of the approach varies with the angle of the cross-over. Another method is to put in a drop center rail (Fig. 7) in the main contact rails opposite the switch points. The bottom of inclines to the drop should be opposite the point of switch

in track, the other end of the drop should be back far enough so that the trolley shoe on the car coming through the cross-over will not hit the side of the main rail. The amount of drop in rail should be sufficient so that a shoe hanging in its free position over the rail will not touch the rail in the drop. The drop rail method is the best, providing there is nothing to interfere with its use, such as lack of clearance between bottom of rail at drop and the ground, switch rods, etc.

In laying out a storage yard with a number of tracks coming off of one or more lead tracks, the contact rail layout requires careful consideration otherwise it may be found impossible to put in sufficient contact rail to provide for proper operation. It is desirable to have a continuous contact surface. This may be accomplished by using a side incline opposite each turn-out switchpoint, or if the yard track centers are not too close, a drop center rail may be used opposite each turn-out switchpoint. This requires that the distance from heel of switch to point of switch on adjacent track should be greater than the distance center to center of trolley shoes on a car. If the track centers will not allow this arrangement it may be possible to use a combination of side incline and drop center, one of these being installed at every other switch point. If a ladder track is used in a yard with double slip switches turning out from each side of this track the contact rail problem becomes very complicated and practically impossible to carry out if the track centers are made too close. The critical distance is determined by the center to center distance of trolley shoes on the cars. In one case of this kind with an old yard having 11-ft. track centers and a ladder track, it was necessary to take out every other slip switch and make its track a turn-out of the adjacent track in order to be able to put sufficient contact rail on the ladder track. Around special work it is often necessary to use a number of short pieces of rail. These should never be shorter than the distance center to center of the shoes on a car otherwise a car may stop in such a position that both shoes may be off the rail with a piece of rail between these shoes. This is called a straddle gap. This will make the time between losing and restoring power on a car very short so that in many cases the automatic control apparatus does not have time to drop out and the equipment will receive a heavy jar. In making section or other open gaps out on the line this time element of the control apparatus on cars should be given consideration together with the speed of car at that

point so that the time elapsing between losing power and picking it up again will allow the control equipment to drop out, thus protecting the car equipment.

Method of Connecting at Crossings. On surface track or elevated track on solid fill, where it is necessary for one reason or another to leave out a piece of contact rail, such as at an expansion gap, cross-over, etc., it becomes necessary to make the circuit continuous by using an underground cable installed in one of the two following methods.

First, using clay or fiber duct or iron pipe, pulling the cable into this and terminating at each end with a cable terminal for protection against break down and enclosing the device with some kind of insulating and weather protecting casing. (Fig. 8).

Second, using a steel taped or wire protected lead covered and rubber insulated cable, commonly called submarine cable, buried in the ground without using ducts and terminating it with a cable terminal similar to that described above. The connection between these cable terminals and the rail to be made with short cable jumpers having enough slack to take care of expansion and contraction of rail. This second method is considerably cheaper than the first and is very satisfactory where there is no possibility of having to dig up a paved street if trouble should occur in the cable. Around yards it is necessary to have many short cable connections between various rails and for this purpose the submarine cable works out very satisfactorily and it can be attached to the rail without the use of a cable terminal by making a short bend on the top and properly taping and painting to prevent water from getting into the cable. This will require more careful maintenance than where cable terminals are used.

Cost of Installation and Maintenance. The cost of installation of contact rail will vary with the local conditions, such as weight of rail required, whether the work is to be done on surface, solid fill elevated track, or elevated track on steel structure. The amount of rail required will determine the price of rail to some extent and since this is the largest individual item entering into the cost of the installation, the cost of the job will depend on this and vary considerably. The working conditions, such as outlined above, will determine the cost of labor. The estimated costs given herewith are based on the assumption that over 500 tons of rail will be required and the working conditions are the average that are met with on surface track.

Cost per mile of single track, using 80-lb. A. S. C. E. standard rail in 60-ft. length.

5,280 ft.	80-lb.—60-ft. steel—70.4 tons	@ $27.40	$1,928.96
8	80-lb.—End inclines	@ 4.75	38.00
92	Pairs 4-bolt fish plates	@ 1.00	92.00
704	Insulating chairs	@ .75	528.00
176	400,000-cir. mil. bonds	@ .90	158.40
2,112	Lag screws	@ .01	21.12
4	Anchors	@ 5.00	20.00
368	Bolts and lock washers	@ .03	11.04
4	Connecting cables	@ 40.00	160.00
704	Sawed Ties (Additional Cost)	@ .50	352.00
			$3,309.52

LABOR:

Transportation and delivering rail to job	$ 35.00
Drilling rail for bonds	52.80
Setting up rail and insulators	96.80
Installing bonds and plates	123.20
Installing and connecting cables	25.00
Incidental Labor	20.00
	$352.80

Total labor and material	$3,662.32
Engineering and supervision 10 per cent	366.23
Grand total cost	$4,028.55

Cost per mile of single track using 50-lb. A. S. C. E. rail in 30-ft. lengths.

5,280 ft.	50-lb.—30-ft. Bessemer steel—44.0 tons	@ $25.50	$1,126.40
180	4-bolt splice bars	@ .75	135.00
8	50-lb. inclines	@ 3.80	30.40
704	Insulating chairs	@ .75	528.00
364	4/0 bonds	@ .45	163.80
2,112	Lag screws	@ .01	21.12
4	Anchors	@ 5.00	20.00
720	Bolts and lock washers	@ .03	21.60
4	Connecting cables	@ 27.30	109.20
704	Sawed ties (additional cost)	@ .50	352.00
			$2,507.52

LABOR:

Transporting and distributing rail	$ 30.00
Drilling rail for bonds	88.00
Setting up rail and insulators	96.80
Installing bonds and plates	218.40
Installing and connecting cable	25.00
Incidentals	20.00
	$ 478.20

Total labor and material	$2,985.72
Engineering and supervision 10 per cent	298.57
Grand total cost	$3,284.29

The cost of maintaining contact rail will vary during the life of the installation from a very low figure during the first few years to a maximum during the rehabilitation period when the installation reaches a point where it must be practically re-

newed, or ties become rotted so that they will not hold the lag screws used to fasten down insulators. It will depend on the weight of rail used, condition of road bed and will also depend on the working conditions under which the necessary maintenance will have to be done. Where it is necessary to have traffic diverted from a track in order to do such heavy maintenance as may require temporary openings or joints, etc., on a high speed road the cost will go up very fast since the labor required to do this may even exceed the actual maintenance labor. With rail of 80 lb. (32.28 kg.) or greater weight on a well ballasted roadbed the maintenance for five or six years will be practically nothing with the exception of periodic inspection which should be made to catch any defects before they become serious, such as loosening up of the joint plates, replacing a defective insulator, shifting of alignment and breaking of bond. After this length of time the amount of maintenance will begin to increase due to wearing out of inclines, rusting out of joint bolts, etc. At an average cost of $80.00 per mile per year the contact rail can be kept in first class condition and the insulation changed every 12 years, which is about the life under ordinary conditions. This, however, does not include complete renewal of rail, plates and bonds, such as will occur when the rail is completely worn out, but does include the usual maintenance of these items in order to keep them in good condition during the life of the rail.

The costs of installation and maintenance as given in this paper are marked as estimates, but they are from the actual figures taken from the books of the operating company. Inasmuch as the work has been done under varying local conditions, the actual figures for various parts of the work have been revised so as to give the cost as it would be under the average conditions met with.

The maintenance figure of $80 per mile is arrived at by this same method. The actual cost of maintenance on the road concerned has been in some doubt during the last two years on account of heavy rehabilitation, but the $80 per year is our experience of what is required for maintenance costs of the third rail contact system during the life of an installation.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., July 1, 1915.

THE CONTACT SYSTEM OF THE SOUTHERN PACIFIC COMPANY PORTLAND DIVISION

BY PAUL LEBENBAUM

ABSTRACT OF PAPER

The paper describes in detail the overhead contact system of the electrified lines of the Southern Pacific Company, Portland Division, which operates at a potential of 1550 volts. The design and materials of construction are given in considerable detail, and the cost per mile, of material and labor, are tabulated in very complete form.

INTRODUCTORY

THE ELECTRIFIED lines of the Southern Pacific Company, Portland Division, extend from Portland to Whiteson, a distance via Forest Grove of 54.0 miles and via Newberg of 45.2 miles, with a line from Cook to Beaverton 7.4 miles long, the map, Fig. 1, showing the extent of the present electrification and also the ultimate plan. All these had been operated by steam for many years. At Hillsboro, Forest Grove, and Newberg, detours from the main line permitting electric trains to pass through the center of these three more important towns were constructed; inclusive of detours, the total miles of main line single track is 104.0, with approximately 16 miles of electrified second track and sidings.

Except for three miles of 600-volt trolley in Portland, the operating potential is 1550 volts.

GENERAL

Construction was actively undertaken in July 1912 and the lines put into operation in January 1914. To account in some measure for the time taken to complete the contact system it may be said that labor troubles caused a shut-down of all work for two months in the Spring of 1913, and that delays in the delivery of car bodies and equipment made it expedient not to push the construction towards the end.

The electrification work was carried on during the operation of the road by steam, resulting in much "lost time" due to

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the distance between sidings and the lack of frequent telegraph stations.

In general, side bracket type of catenary construction, Fig. 2, is employed, the poles being placed on the outer side of curves. High-tension transmission lines (13,200-volt) are carried on the same poles as the contact system between Oswego and Dundee and between Oswego and Forest Frove, via Beaverton, their total length being 47 miles. In order to maintain the transmission line on one side of the track, cross-span construction is used where the poles come on the inside of curves. Figs. 2,

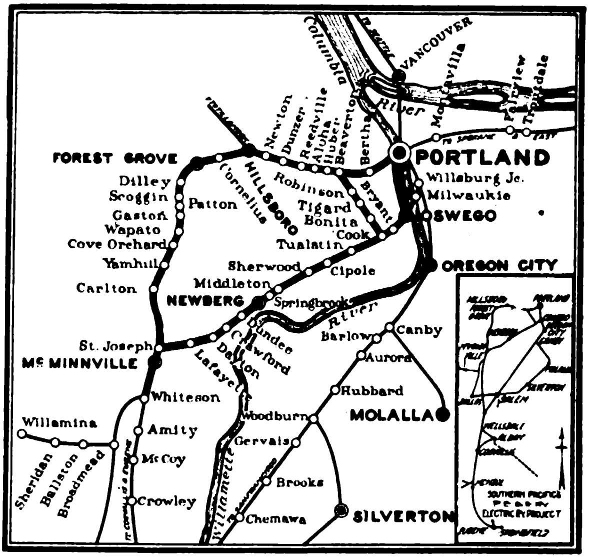


Fig. 1—Electrification of First Unit Southern Pacific Lines in Oregon—Under Auspices of Portland, Eugene and Eastern Railway

3, and 4 illustrate this type of joint construction, the latter figure being taken between Oswego and Cook, where the transmission lines parallel each other for a distance of four miles.

The standard pole spacing on tangents is 150 feet. As seen from Table I, however, over 25 per cent of the main line mileage is curved track, the portion between Sherwood and Springbrook being exceedingly crooked; on this account, as well as on account of siding and cross-span construction, 5666 poles were used, or an average of 54 poles per mile. Construction was further made more difficult by the presence of 25,204 ft.

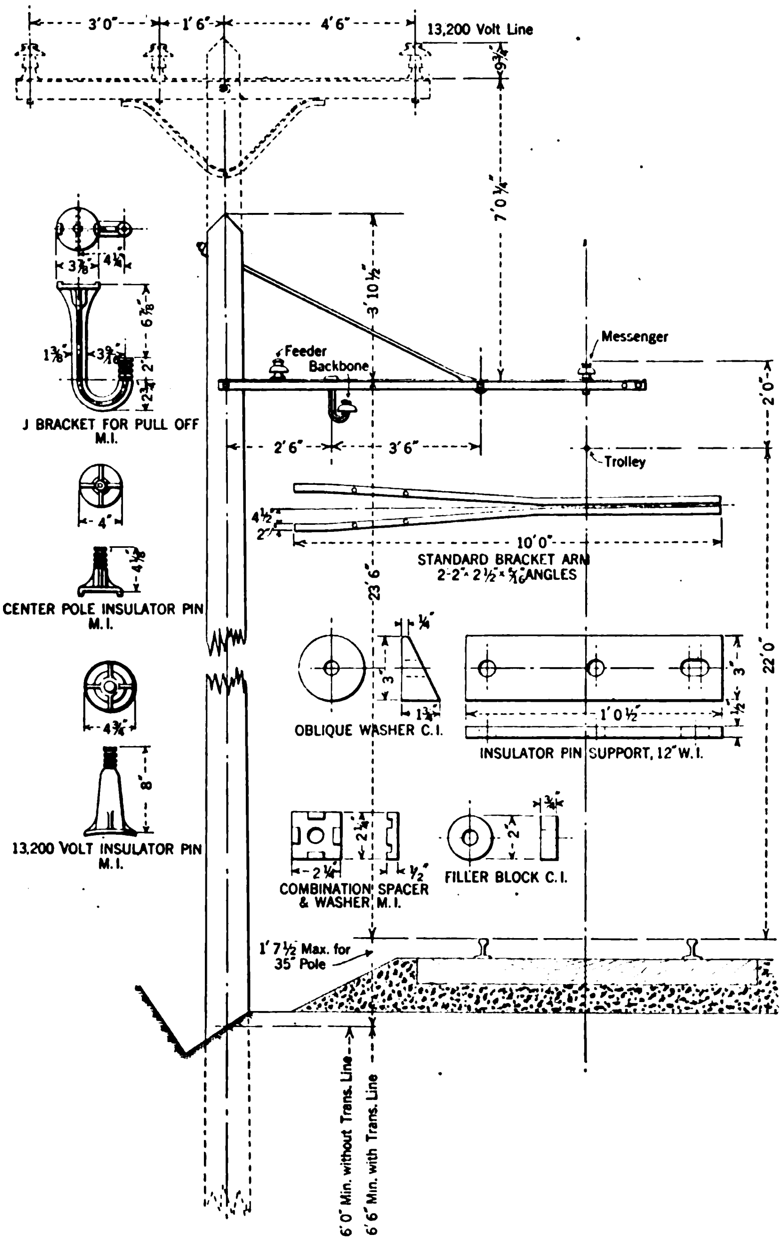


FIG. 2—STANDARD BRACKET ARM CONSTRUCTION—MCMINNVILLE LOOP

of trestle, of such height as to make support of the pole on the trestle a necessity.

TABLE I.

Degree of curve	Pole spacing	Total length of curves.
0–2	150 ft	57,870 ft
2–4	120 "	37,695 "
4–6	90 "	20,627 "
6–8	60 "	7,345 "
8–10	60 "	7,412 "
10–15	60 "	8,568 "
		139,517 ft. = 26.4 mi.

In the following, the costs due to the presence of a high-tension line on the poles supporting the contact system have been eliminated as not being relevant.

Poles. All poles are nominal 9-inch top, cedar poles, purchased under specifications that required a top circumference between $27\frac{1}{4}$ inches and $32\frac{1}{4}$ inches, and subject to inspection at destination; it was found that, unless some limitations were placed on contractors, the term "9-inch top" was very flexible.

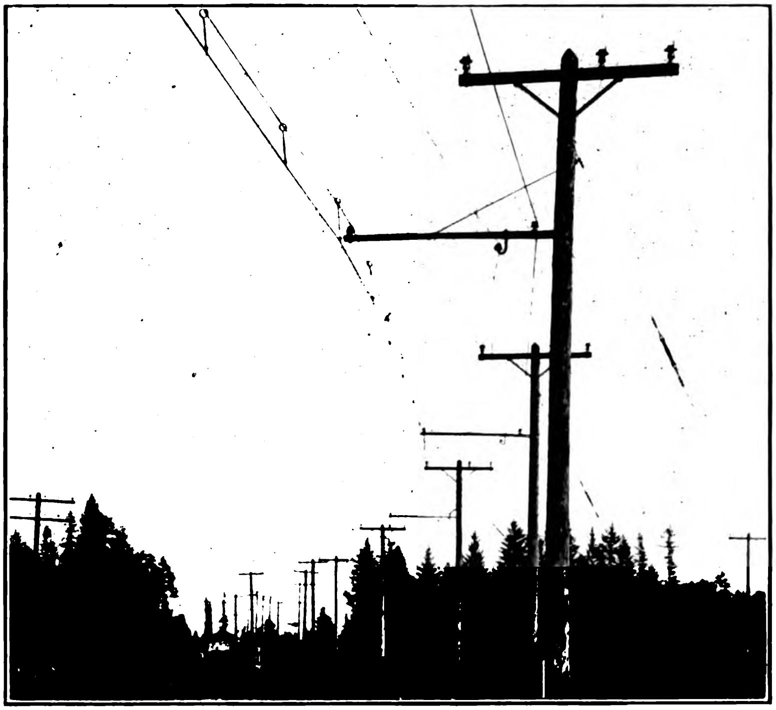
The standard pole length for catenary construction is 35 ft; for transmission and catenary, 40 ft; local conditions, such as crossing of telephone and telegraph lines by the transmission line, increased these lengths.

Table II indicates the items that are included in the cost of the pole at the hole.

TABLE II.

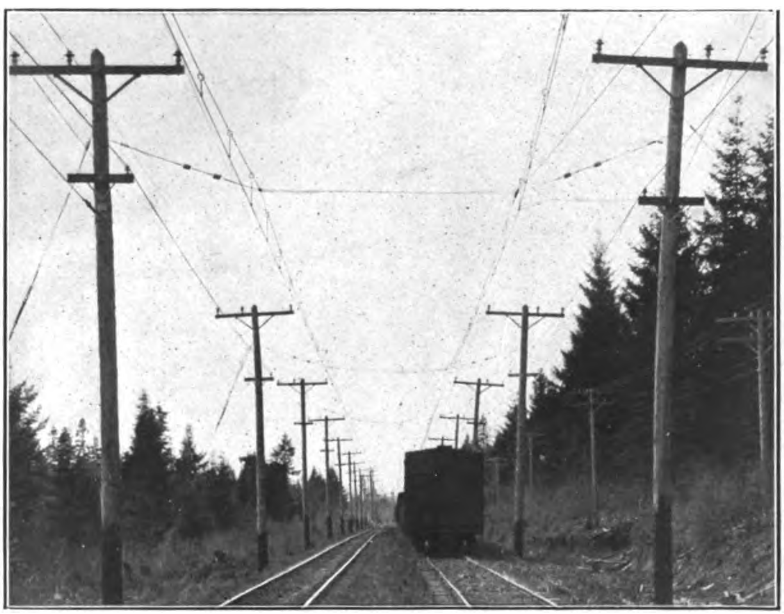
Length of pole, ft.	35	40	45	50	55
Cost, f.o.b. company yard	$4.20	$4.80	$5.40	$6.00	$6.60
Cost, handling in and out	0.20	0.20	0.25	0.25	0.30
Cost, framing and shaving	0.55	0.55	0.60	0.60	0.65
Cost of treating	1.25	1.25	1.25	1.25	1.25
Cost of distributing	0.70	0.70	0.75	0.75	0.80
Cost of pole at hole	$6.90	$7.50	$8.25	$8.85	$9.60

All poles were given two thorough brush treatments with carbolineum avenarius, from a point 18 inches above the ground



[LEBENBAUM]

FIG. 3—CURVE CONSTRUCTION—SINGLE-TRACK CATENARY WITH 13,200-VOLT TRANSMISSION LINE



[LEBENBAUM]

FIG. 4—DOUBLE-TRACK CATENARY CONSTRUCTION WITH TWO 13,200-VOLT TRANSMISSION LINES

to within three feet of the butt. The preservative was applied by means of burlap fastened to the ends of long mop handles and was kept hot by steam coils placed on the bottom of the shallow tank over which the poles were rolled. Steam was furnished from a locomotive and approximately one gallon of preservative (including losses due to leakage from barrels and evaporation) was used per pole. Costs include labor, ($0.50), material, rental of locomotives and first cost of tank. Distributing costs include work train and flat car rental.

Contact System. The details of the materials used in the support of the contact system were developed by the Southern Pacific Company on its 1200-volt suburban system at Oak-

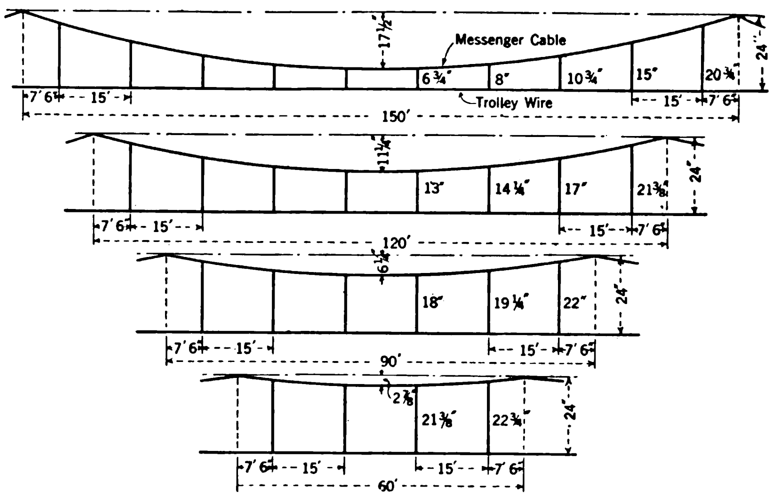


FIG. 5—TYPICAL CATENARY SPANS—INTERURBAN CONSTRUCTION

land, Cal., some slight modifications being made to meet local conditions.

Pole and line material is galvanized or sherardized, all bolts and nuts being given the latter treatment. The increased cost of galvanized material was deemed to be warranted on account of increased life and decreased up-keep in a region where rains, winter and summer, are of frequent occurrence.

The messenger cable is 7/16-inch high-strength (crucible) steel strand, (15,000 lb. breaking strength), strung at a tension of approximately 2200 lb. at 70 deg. fahr., which gives sags and hanger lengths as shown in Fig. 5. The tension in the 4/0 grooved copper trolley wire is 2000 lb. A construction

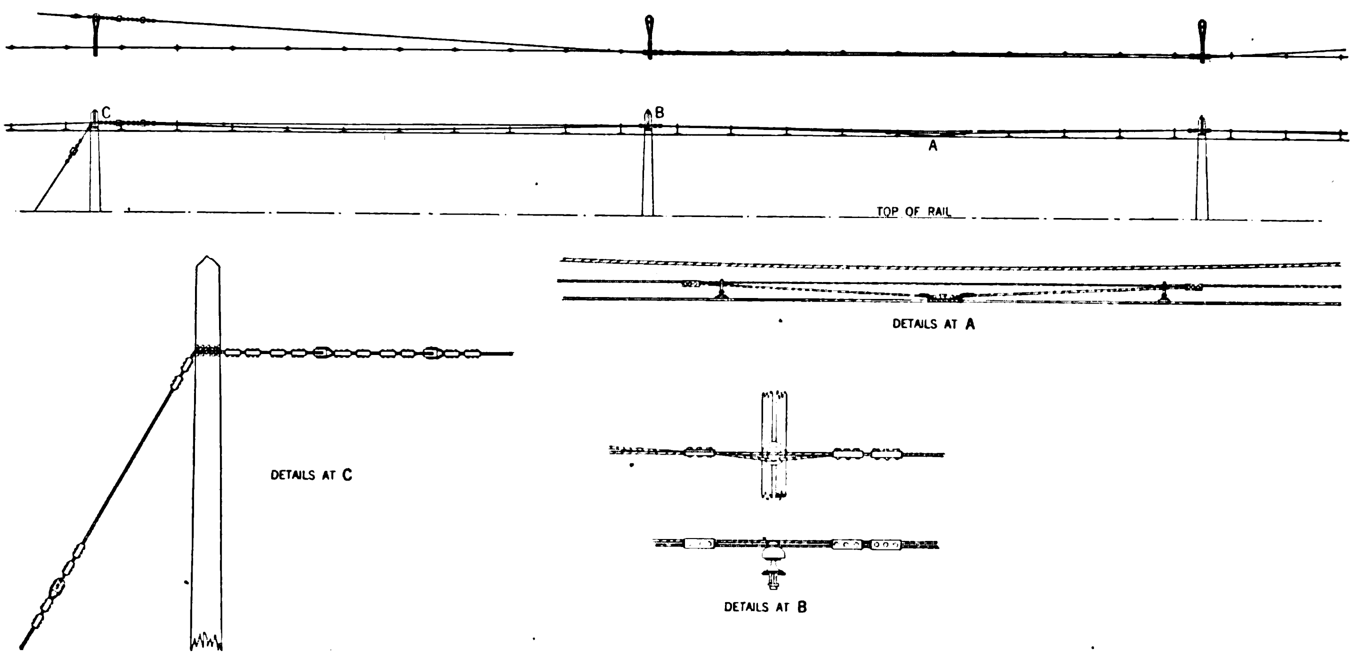


FIG. 6—LINE ANCHOR

1. Line anchor—7/16 in. H. S. steel cable. 2. Messenger cable—7/16 in. H. S. steel cable. 3. Trolley wire—4/0 grooved. 4. Trolley anchor—5/16 in. bessemer steel cable. 5. Three bolt guy clamp. 6. Porcelain strain insulator. 7. Strain ear—12 in. 8. Back guy—7/16 in. H. S. steel cable.

train was used to erect the messenger and trolley wires and to clip in the hangers.

Under maximum loads (ice, sleet and wind), the tension in the messenger is calculated not to exceed the elastic limit, climatic conditions being such that the minimum temperature rarely falls below 20 deg. fahr. Ice and sleet are unusual.

Hangers (Fig. 9) are installed at 15 ft. intervals; they afford a very flexible connection between the messenger and trolley, have a minimum number of parts and are used interchangeably on tangents and curves. As first installed, the locknut was omitted. The threads on the rods, due to the vibration of the line, began to strip, and the locknut was added to over-

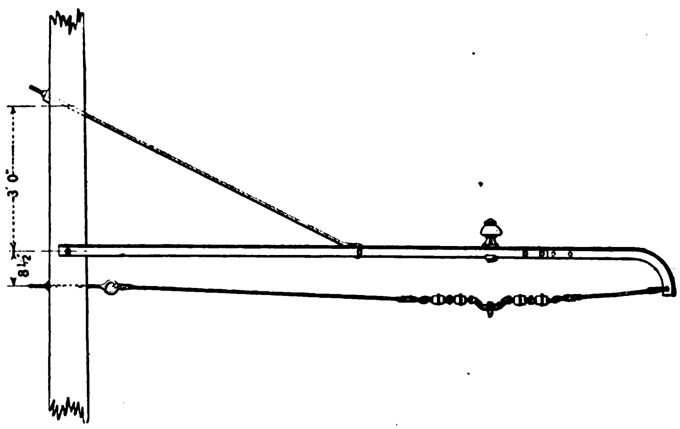


FIG. 7—TROLLEY WIRE STEADY—BRACKET CONSTRUCTION

come this trouble, which it has done. The standard 150-ft. span weighs 1.152 lb. per foot.

A mechanical clamp holds the messenger in the groove of the insulator, and prevents slipping in the event of line trouble. The contact system is further anchored every half-mile on tangents, as shown in Fig. 6, and against a curve at each end thereof, so as to take the strain out of the curve. Steady braces, Fig. 7, were installed every half mile, after the system was placed in operation, they being found a necessity; on curves, the pull-offs have a steadying effect.

The line is sectionalized at all junction points, at substations, and where the voltage changes from 1550 to 600, a sectionalizing insulator of the type shown in Fig. 8 being used. On ac-

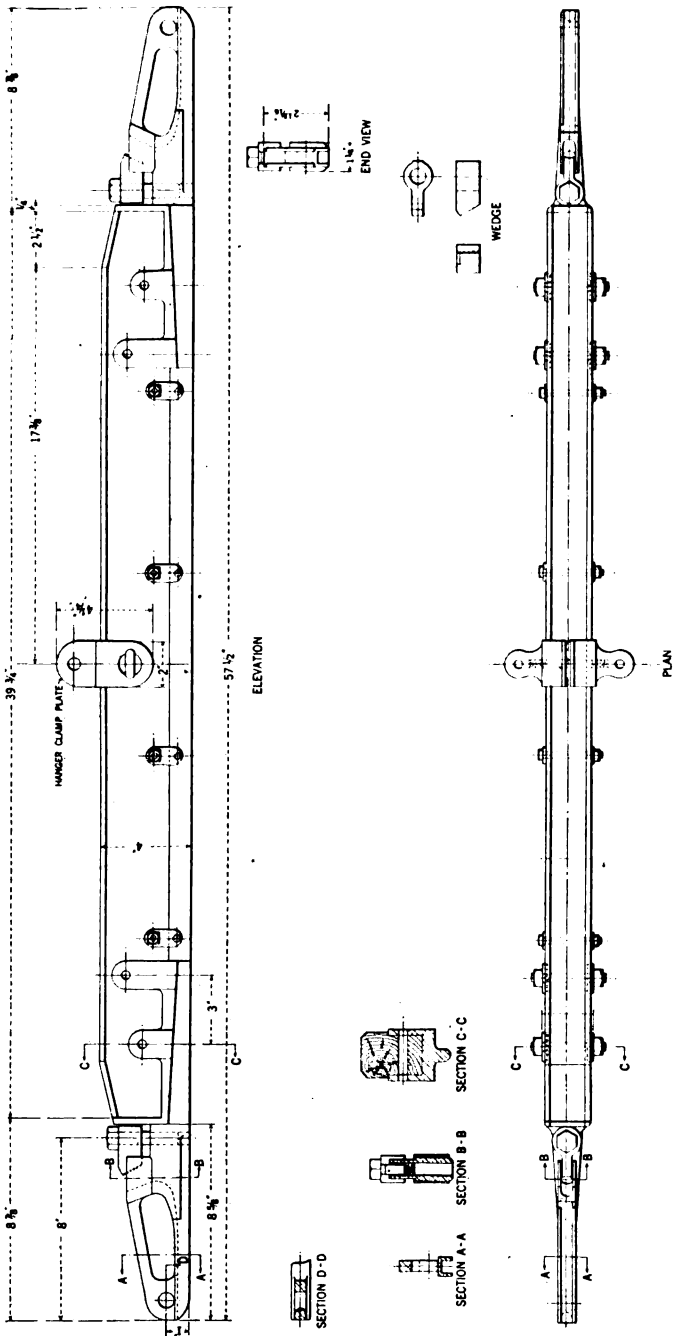


FIG. 8—TROLLEY SECTION INSULATOR

count of the hard spot introduced in the line by this device, a section break, consisting of two parallel wires suitably insulated from each other, is being developed.

Table III indicates the cost of a mile of tangent construction as illustrated and described in the foregoing.

TABLE III.

	Ref.	Tangent	
		Units	Cost
Material.			
Poles—35 ft. long	Table II	35	$ 147.00
Bracket arms complete	Fig. 2	35	197.00
Steel strand–7/16 in. high strength		6500 ft.	149.00
Line anchors	Fig. 6	2	70.00
4/0 copper trolley wire		3400 lb.	780.00
Hangers	Fig. 9	360	90.00
Steady braces	Fig. 7	2	5.00
Miscellaneous material			25.00
Feeder insulator and support	Fig. 2	35	37.00
Per mile			$1500.00
Labor.			
Handling, treating, distributing	Table II	35	95.00
Digging holes		35	60.00
Setting complete with bracket		35	70.00
Stringing messenger and trolley			55.00
Installing hangers			50.00
Installing anchors		2	20.00
Lost time a/c laying in at sidings			75.00
Adjusting and dressing line			50.00
Work train			125.00
Per mile			$600.00
Total per mile			$2100.00

To the above must be added the usual percentages for engineering, superintendence, and contingencies.

Curves and sidings for the division under consideration, increased these costs about 20 per cent, so that the cost of the average mile of main line track (excluding the section between Sherwood and Springbrook, where excessive curvature greatly increased construction costs) was $2550.00. This figure makes no allowance for construction on trestles, which is deemed a very local condition, and is therefore not included.

A large proportion of the holes were dug in earth and under fairly favorable conditions. Rain, and water in the holes, at times interfered with digging.

Men lived in outfit cars, rental of which is included in all labor costs; gasoline section cars or work trains were used to transport the crews to and from work, the average run being not more than three miles.

Rates of pay on line construction were as follows: Foremen, $125.00 per month; linemen, $4.50, groundmen, $2.75 to $3.00, and common labor $2.25 to $2.50; all per day of 9 hours, one way on company time. Overtime was at the rate of $1\frac{1}{2}$ the standard time. Work trains, including locomotive and crew, are rented to the construction department at a rate of approximately $40.00 per day.

In analyzing costs of material, attention is called to the fact

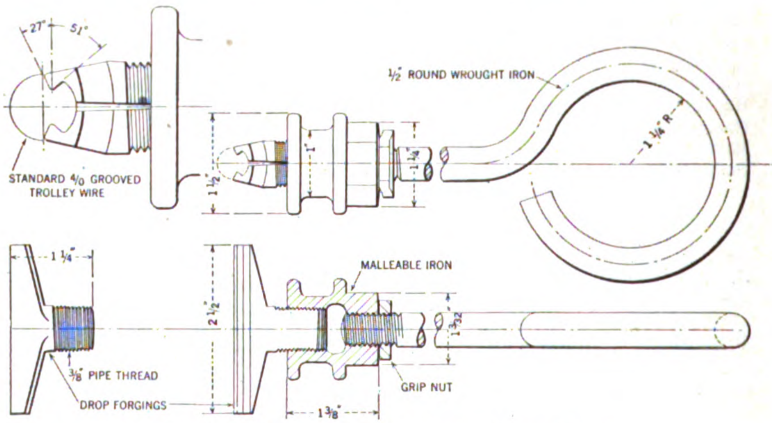


Fig. 9—Catenary Hanger—Loop Type

that freight is an important item, especially on steel products, for Pacific Coast conditions.

Feeder supports, but no feeder, are included in the above costs. This item will vary with substation spacing, line voltage and traffic conditions.

Curve Construction. Flexibility is extremely desirable in a contact system from which current is taken by roller pantagraphs, on account of the inertia of the collector, and at no place in the line is this more evident than at curves.

As first constructed, pull-offs of 5/16-inch steel strand (3800 lb. breaking strength) were used between the backbone and the catenary system, and a maximum deviation on curves of six inches from center line of track was allowed. It was found that a pull-off of this size was too stiff, especially on the lighter

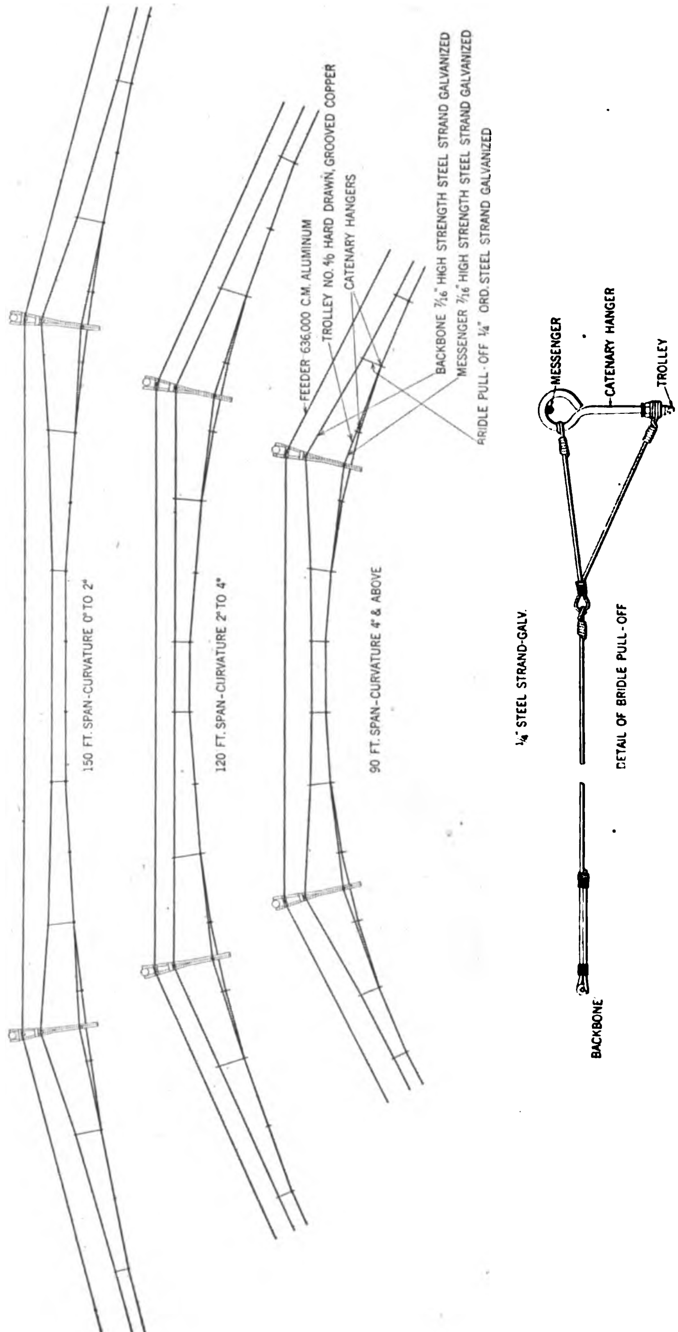


FIG. 10—CURVE PULL-OFF CONSTRUCTION

curves (up to six degrees), and ¼-inch strand (2300 lb. breaking strength) is being substituted. Pull-offs were first installed on hangers adjacent to the brackets; but are now being installed in accordance with Fig. 10; this makes for increased flexibility.

The bracket, Fig. 2, is used to insulate and carry the backbone on light curves, Fig. 3 illustrating this type of curve construction. On heavier curves, the backbone is fastened to the back of the pole and the pull-offs are insulated from the backbone in the manner shown in Fig. 11; this illustration further shows a type of simple trolley construction that has been found very suitable for pantagraph operation.

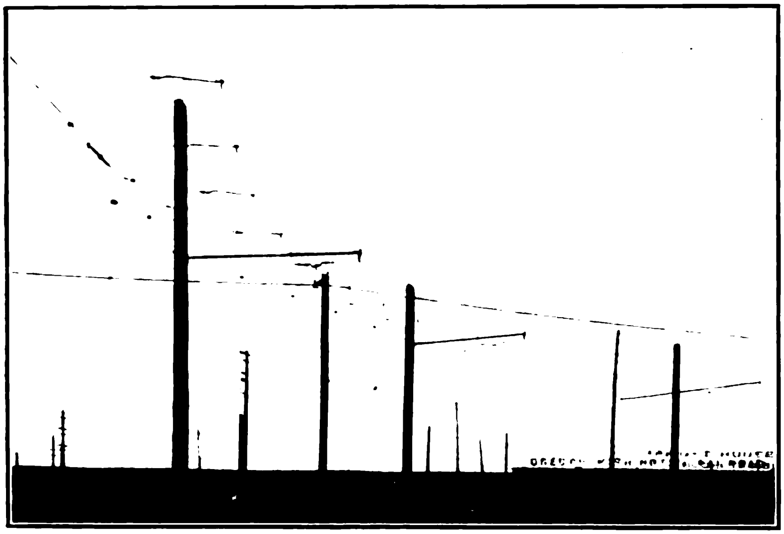
Maintenance. The system was placed in operation on Jan. 18, 1914. Three crews were at work on construction for several months following, when one crew was laid off. The second crew was laid off on October 1, 1914, the crews up to this time having been partly on maintenance and mostly on work chargeable to construction. The following figures on maintenance therefore apply only to the period from October 1, 1914, to March 31, 1915; the contact system being almost new.

TABLE IV.

Acct. No.	Material	Labor	Total
9 Cars	$33.00	$50.00	$83.00
20 Poles	7.00	68.00	75.00
22-1 Feeder	4.00	64.00	68.00
22-3 Trolley	23.00	428.00	451.00
Total per Month	$67.00	$610.00	$677.00
" " Year	$804.00	$7320.00	$8124.00
" " mile per year (104 mi.)	$7.73	$70.38	$78.11

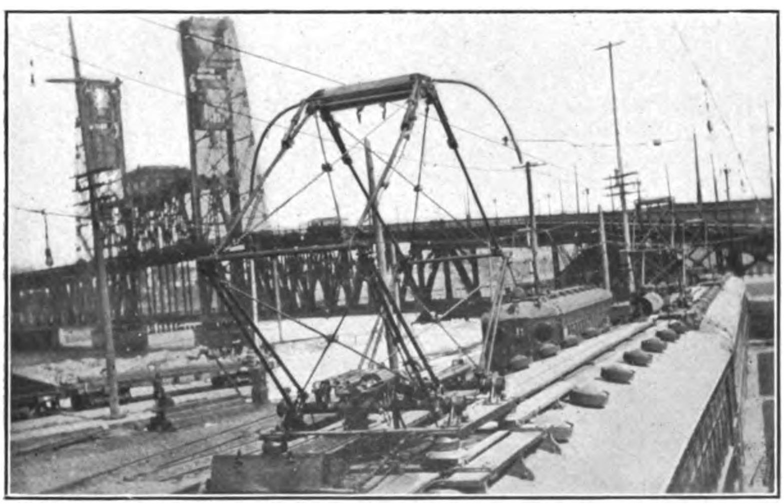
The maintenance crew consists of one foreman ($135.00 per month), three linemen, ($4.50 per day), and four groundmen ($3.00 per day), and has its headquarters at Oswego. Each man gets one day off per week.

In addition to maintaining the contact system, this crew handles all repairs to the 13,200-volt transmission line and 2.5 miles of 60,000-volt transmission line, about 6 per cent labor



[LEBENBAUM]

FIG. 11—CURVE CONSTRUCTION—SIMPLE TROLLEY—UNION DEPOT TERMINAL YARD



[LEBENBAUM]

FIG. 12

in addition to that shown in the above tabulation being chargeable to this item, (Acct. No. 49).

Gasoline section motor cars, equipped with towers, are used for maintenance, the crew, where possible, taking regular trains to get to and from work. Account No. 9 in Table IV, gives the cost of operating and maintaining the gasoline cars, of which five are in use; the men keeping their own cars in repairs to as great extent as possible.

Because of the short period under operation, it is hardly possible to analyze the work done in maintaining the lines, say as between hangers, messenger, trolley, feeders or special devices, such as crossings, section insulators, steady braces, etc.

As an indication of the use made of the contact system, the following figures are given:

Average train miles per day	1460
Average motor car miles per day	3041
Average trail car miles per day	560
Weight of motor car, tons	53
Weight of trail car, tons	35
Schedule speed, mi. per hr	20
Average running current per motor car	200

Current Collectors. In closing, a few words may be of interest as regards the results being obtained with the current collectors, shown in Fig. 12. An improved system of lubrication, was devised by Mr. E. Sears, Supt. of Electrical Equipment; this, together with the substitution of roller bearings for the graphite bushings originally furnished, has made possible the following costs per 1000 motor car miles for the period Jan. 1, 1915 to April 14, 1915.

TABLE V.

	Total	Per 1000 motor car miles.
Lubrication	$1.01	$0.0058
Material repairing	17.82	0.1022
Labor repairing	36.27	0.2080
Labor inspecting	15.09	0.0865
Total	$70.19	$0.4025

"Welsh" oil, at 14 cents per gallon, is used for lubrication.

Collectors are made of five-inch (outside diameter) steel tubing with 7/32-inch wall, and operate at a pressure against the wire of from 30 to 35 lb. A defective quality of tubing was originally furnished, the cost of replacing some of which is included in the above tabulation; this has resulted in keeping the average mileage per collector down to 9696. As soon as the defective tubing is weeded out, it is hoped to materially increase this mileage.

The wear on the trolley wire to date has been inappreciable.

DISCUSSION ON "PROTECTIVE REACTORS FOR FEEDER CIRCUITS OF LARGE CITY POWER SYSTEMS" (LYMAN, PERRY AND ROSSMAN) AND "USE OF REACTANCE WITH SYNCHRONOUS CONVERTERS," (YARDLEY) NEW YORK, OCTOBER 9, 1915. (SEE PROCEEDINGS FOR NOVEMBER, 1915.)

(Subject to final revision for the Transactions.)

D. B. Rushmore: It is very difficult to consider the subject of reactors for power stations or feeders without studying the apparatus such as generators, transformers, oil switches, protecting apparatus, etc.

As a rule, electrical disturbances are due either to high currents, high voltages or high frequencies; and high frequencies have, as a rule, an indirect effect of producing high voltages, so we have simply high currents and high voltages to contend with.

The use of reactors as a protection against high voltages is well known, and I take it as rather outside of the subject of the papers tonight; so we come down to the use of reactors as protective devices against high currents, and this is a subject which is comparatively new.

Those who have been associated with the building of transformers, know it is only a very few years since competition was based on excellencies of regulation. The transformers that regulated 1½ per cent were supposed to be very much better than those which regulated 2½ per cent. Now, however, the customer frequently specifies that the transformers must contain six or eight per cent reactance and even higher.

In designing generators, transformers, and to some extent converters and other synchronous apparatus, if you design for commutation and heating there will be a natural reactance that will fit these conditions, and without an abnormal design you cannot vary these reactances beyond a certain point. It is therefore a question discussed in many cases as to how much internal and how much external reactance there shall be.

The use of reactors in power stations also involves a study of feeder reactors, because one is so dependent upon the other. The injurious effect which these reactors are supposed to protect against are, first the incidental rush of current, which is destructive to the windings and brings tremendous mechanical forces to bear thereon. Secondly, there is the heating effect, and it has been necessary to investigate to some extent the time which apparatus will stand very abnormal heating conditions when there is practically no chance for the dissipation of heat, but simply its absorption in the material in which it is originally generated.

Reactance is an evil; it is a necessary evil in some cases, but what we want is a reactance which is only there when it is required; so if someone will invent a reactance which is not a reactance until it is wanted, we will be greatly helped. That is, a reactance which is very low until the current exceeds a certain amount, and then is automatically raised to a very high value.

Philip Torchio: We hear so much talk of reactance now, because we neglected to take into account its importance in the past. For instance, very few of us used to consider when we compared the breaking capacity of a switch whether the short circuit was on a 25-cycle generator, or a 60-cycle generator. Provided it was the same capacity generator, we would have expected that the short circuit effect would be the same. But it makes a large difference in a feeder short circuit whether the current is 25-cycle or 60-cycle. At 60 cycles the reactance of the feeder would be 2.4 times that at 25-cycles, and the effect of short circuit would therefore be much different in the two cases.

I think the authors have covered pretty fully the benefits and advantages obtained from the use of reactances on feeders. I wish to add a few statements which have been perhaps omitted. One is, that the energy loss in feeder reactors is extremely small, and amounts to less than 1/10 of one per cent on 60-cycle, and less than $\frac{1}{6}$ of one per cent on 25-cycle transmitted power for a $3\frac{1}{2}$ per cent reactance.

In addition to limiting the current flowing into a feeder short circuit, the feeder reactance further increases the continuity of supply by preventing the generator bus voltage from materially dropping. As an example: Assume the 150,000-kv-a. bus with 8 per cent generator reactance given in the paper, with 5000-kv-a. feeders having 3 per cent reactance. The maximum feeder short circuit would cause only a momentary 9 per cent drop in the bus voltage. This is very essential in holding all of the synchronous apparatus in step on the system.

In very large systems the question of limitation in rupturing capacity of oil switches is a burning question. In this respect a 2 per cent or 3 per cent limiting reactance on the feeders would ensure the opening of the feeder short circuit under all conditions, without the least strain on the switch, or interference with the rest of the service.

The New York lighting companies found from their experience that some of the few serious generating station troubles were occasioned by failures of high-voltage motors driving auxiliary apparatus like station exciters, etc.

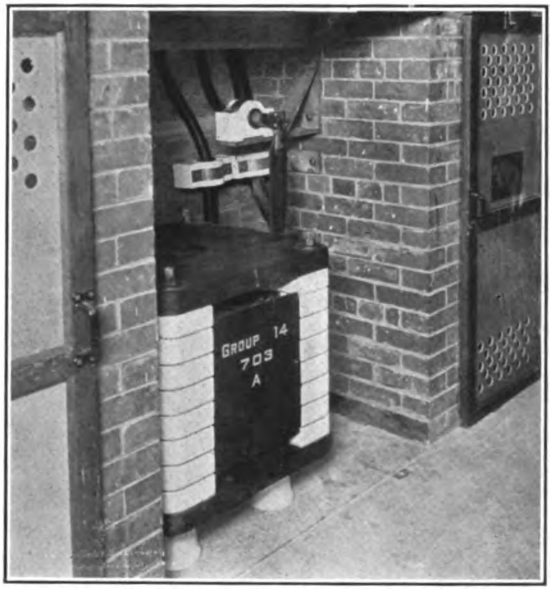
Recognizing this fact, they were pioneers in the use of feeder reactors by equipping all of the feeders supplying generating station auxiliaries with reactors, which have proved to eliminate entirely all of the serious troubles from that source.

Fig. 1 gives an illustration of such an installation showing three sets of 250-kw. 8000-volt motor-generator exciters, each equipped with 2.5-kv-a. reactors.

The first station designed and equipped for busbar reactors and feeder reactors is the 201st Street station of The United Electric Light & Power Company, having an ultimate capacity of 130,000 kw., 8000 volts, three-phase, 60 cycles. Between each section of busses there are installed 18 per cent reactors (based on 30,000 kv-a.), and on each 4000 kv-a. feeder $3\frac{1}{2}$ per

[TORCHIO]

FIG. 1



[TORCHIO]

FIG. 2

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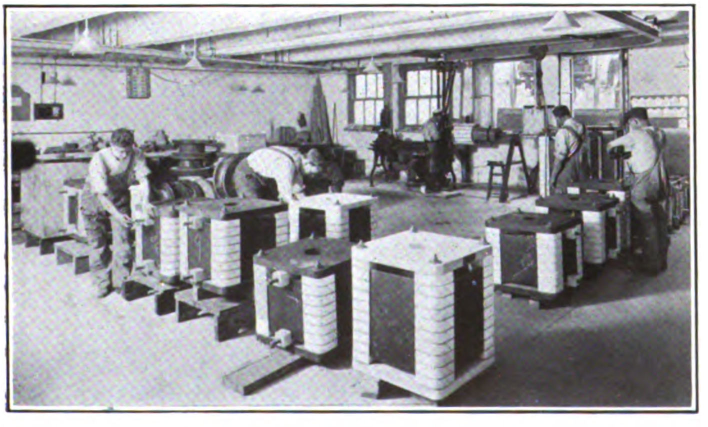
FIG. 3



[TORCHIO]

FIG. 4

cent reactors. The feeders are arranged in groups of two, each group being fed from a group switch. There are only two reactance coils for each feeder.

Fig. 2 shows one coil of one feeder in the front compartment, while the other coil is in the back compartment. In each of these compartments and on top of the existing coil there is a vacant space for the addition of a second coil for the second feeder not yet installed.

Fig. 3 shows a compartment with the double coil for the two feeders, both feeders of this group being already installed. On the right side are shown the terminals of the reactors through porcelain bushings.

Fig. 4 shows perhaps more in detail the construction of the feeder reactors and illustrates also the method of winding of the coil which, after being saturated and baked, is placed in the holder with porcelain supports at top and bottom and sides, and ebonized asbestos board panel enclosures, for safety to apparatus and men.

In this connection I wish to lay stress upon the point of using insulated windings for the reactors. Coils with bare windings do not appear to me to be in keeping with the scrupulous separation by barriers and insulation of all high-tension conductors and wiring of a modern switchboard. Furthermore, I think that some insulation is necessary to protect the windings from foreign substances, vapors, accidental moisture and vermin. The difference in cost between bare windings and insulated windings is very trifling. The idea that bare windings can withstand higher temperature and therefore are safer is misleading, because it overlooks the fact that the protective reactance coils is always in circuit with other apparatus, like generator or transformer windings, cables and current transformers, all of which are insulated with fibrous materials and have less facilities to radiate heat than the reactance coils, and would burn out long before the insulation on the reactance coil would suffer.

From an extensive experience with insulated-winding reactors under most diversified conditions in this country and abroad there is not a single instance of failure. Furthermore, some of these reactors have operated for several seasons when covered with soot and dripping wet from rain and snow blown on them under conditions where a bare winding would have undoubtedly failed.

H. W. Buck: This question of reactance is certainly very important in alternating-current circuits, but I do not think that we should allow ourselves to be led to believe that all alternating-current systems should have reactors installed upon them. Simplicity is an excellent engineering goal to steer for, and our alternating-current installations are already too complicated, and reactors still further increase it. The acute necessity for reactance has been brought to our attention within

recent years through the development of such systems as that of the New York Edison Company and the Chicago Edison Company and others, where an enormous amount of power is concentrated in one generating station with the power transmitted over circuits of small inherent reactance, with the consumers located at comparatively short distances from the sources of generated power.

Here reactors are needed to improve the service and to preserve the integrity of the system against damage from abnormal magnetic forces. The enormous momentary flow of current in an alternating-current generator under short circuit, possibly ten or fifteen times what it is at the end of a few seconds, causes magnetic effects which are irresistible with a number of generators connected to the bus bars and with possibilities for destruction in the stations which are very great.

Many instances of such destruction from magnetic forces have been noted and some which I have seen are as follows:

In one case a short circuit took place near a large power house. The busbars which were installed inside of a modern brick structure were blown out by magnetic repulsion through the brick of the surrounding structure, the busbar structure itself was demolished, and the copper of the busbar was blown 40 ft. or 50 ft. from its original location.

In another case, about 24 one-million circular-mil single-conductor cables were racked on the wall of a run-way about 15 ft. wide. A short circuit took place in a manhole near the power house, with the result that every cable in the run-way was torn from the cast iron racks on which they were supported and hurled across the run-way, damaging the masonry on the opposite side.

A third case resulted in a short circuit of a power house of about 60,000 kw. normal capacity. The feeders through which the short-circuit current flowed were of ordinary three-conductor, type, lead covered. Under the magnetic stress prevailing several of the cables exploded, blowing the lead covering to pieces and demolishing sections of the eight-duct conduit in which they were installed.

I mention these instances to show the possibilities of the enormous magnetic mechanical forces which are available momentarily under short circuits from the large power houses, and the necessity of limiting the maximum flow of current under conditions of short circuit by the installation of reactors.

On long distance transmission systems where an overhead line intervenes between the generating station and the point where the power is used, reactance is not needed to prevent destruction at the receiving end, as the line itself necessarily has such high reactance that it automatically limits the flow of current at the terminus of the line to a safe maximum amount. Distribution systems, therefore, which are fed by long-distance transmission need reactors only for the purpose, as stated in

the paper, of controlling the regulation and for limiting the voltage disturbances on the system.

There is an important use of reactors on long-transmission trunk lines where a tap line is connected to the main trunk line, over which a comparatively small amount of power is supplied. Here it may be necessary to limit the amount of current which can flow over the branch line and so prevent its being a menace to the service on the main line. By installing a 5 per cent or 10 per cent reactor in the branch line, the service over the main line is not interrupted, and the effect of short circuit on the branch line is practically negligible to the trunk line service.

It is unquestionably desirable to install reactance coils on such large systems as that of the New York Edison Company to prevent damage from magnetic forces where the service is through three-conductor underground cables of small inherent reactance, where the maximum flow of current is limited only by the ohmic resistance of the circuit.

H. R. Summerhayes: Mr. Buck has just emphasized the necessity for simplicity in alternating-current systems. To my mind we should aim for simplicity in operation, and possibly we may accomplish that by the addition of apparatus in the form of reactors.

In Mr. Yardley's paper it was pointed out that on the Edison d-c. systems of the larger size, in which the whole network is connected in multiple, troubles are local, and they burn themselves out and do not result in a shut-down of the whole, or even of a large portion of the system. In fact, it is seldom that even the synchronous converter is shut down from these short circuits.

I believe the alternating current systems are tending toward the same result. At present most of the large alternating current systems are connected with radial feeders; that is, the feeders are not interconnected. Experience has shown that trouble will result if the feeders are interconnected, in order to use the copper to the best advantage.

I believe that with the use of reactance in the proper localities, and the development of relays that has taken place, it will soon be possible to interconnect these systems and use the copper to better advantage; and that the operation will be similar to that of the direct current system, in that the trouble will be localized.

One point brought out in the paper on feeder reactors, is that the busbar reactors must also be used, owing to the possibility of trouble in the station itself. That I think is a very important point.

There are other methods of using busbar reactors than simply connecting them between the sections, Some of the more recent ideas involve dividing large stations into one section for each generator, and not connecting those sections directly through reactors, but connecting each section through reactors

to a sort of tie bus. This I think is a considerable improvement over older systems.

Mr. Lyman concludes that it would be desirable for many reasons to operate feeders in parallel at their substation ends, but such operation tends to increase greatly the kv-a. flowing into a feeder short circuit and to cause other feeders besides the one affected to trip out when overload relays with the usual settings are used. I would suggest that this conclusion does not apply to all cases. The development in relays makes it possible to operate the switches selectively even where the kv-a. values at short circuit are very high. There are some cases for instance, where it is sufficient to install reverse-power relays at the substation ends of the feeders and selective overload relays at the generating station ends. In other cases different expedients may be necessary. Generally the addition of feeder reactors makes it easier to make the operation of the relays selective.

Mr. Torchio invited discussion on the matter of insulation of reactors. Of course the great advantage of using insulation is that it makes the reactance compact, saving space in the station where space is of importance. The dimensions are reduced, as you do not have to allow such great distances between conductors to prevent surface leakage. On the other hand, the insulation on the conductors introduces a comparatively large amount of inflammable material at a point where it is exposed to the greatest amount of heat; that is, it is right in contact with the conductor, and all the heat must go out through that insulation. In case of weakness at the time of short circuit when the voltage across the reactance is high, a puncture or local flash-over might cause a considerable fire.

Therefore, I believe that insulation on the conductors should be avoided as a rule and used only where special conditions such as high working voltage, large number of turns or limited space for installation make a reactor with bare conductors impracticable.

J. J. Frank: In Mr. Yardley's paper reference is made to an automatic switch operating as a protective device. I question the ultimate value of such a mechanical device as an automatic protection in comparison with the value of the absolutely magnetic device found in these current-limiting reactors.

The controlling feature in the design of current-limiting reactors should be their function as a protection to generators, busbars, and feeder circuits. Every other feature in details of construction should be secondary to this dominating one. Both the mechanical and electrical designs may be widely different on reactors protecting generators and busbars, from those to protect high voltage circuits, as referred to by Mr. Buck.

N. W. Storer: Mr. Rushmore has propounded a conundrum. He believes thoroughly in a larger reactance to keep down the violence of short circuits, as most of us now do, but he wants reactance that is reactance only when it is needed. The co-

nundrum then is, "When is reactance not reactance?" The answer is, "When it is short circuited," and Mr. Yardley's paper has shown us how to secure this kind of reactance. One of the most noteworthy points in his paper is his reference to the tests of a quick acting circuit breaker. I believe that the use of this circuit breaker to short circuit a large part of the external reactance in the circuit will give just the combination that is desired. A certain amount of reactance must be in the circuit all the time, but given a quick acting breaker such as described we can get all the benefit of a large reactance without its bad effects.

George T. Hanchett: When extraneous reactance was first introduced as a protective device, it always appeared to me as a piece of patch work to cover up some of our previous mistakes. As Mr. Rushmore says, early specifications call for regulation par excellence, and having obtained, at great expense, rigidly constant potentials, we begin to counteract these by installing at further expense protective reactance.

We seem to have forgotten that it is very easy to build a transformer or generator so that it will lay down by using more open design larger clearances which facilitate insulation and ventilation and reduce cost. In the case of feeders, particularly where it is desirable to interlock them, trouble flows from feeder to feeder through these interconnections which may well be reactors.

I was visiting the plant of a large transformer company a few days ago and was impressed to observe the tendency to insert magnetic leakage plates in transformers. These facts should be seriously considered when contemplating large reactances for the protection of large generators or transformers. With existing closely designed equipments, reactors are absolutely necessary.

Carl J. Fechheimer: The statement has been frequently made that iron in reactance coils is undesirable as it saturates, such saturation occurring at just the wrong time unless a very large amount of iron is employed. The purpose of reactance coils is to prevent a prohibitively large current flowing; and if the value of reactance decreases as the currents increase in magnitude due to the iron saturating, it fails of its purpose. Therefore, I also believe that in transformers, to which reference has been made, the same effect will come in. Similarly in the construction of generators we should not count on the effect of iron for increasing the reactance, trusting that thereby the great rush of current will be prevented.

It is interesting to note that the magnitude of the current which flows at the first instant on short circuit does not depend only upon the voltage induced just before the short circuit occurs and upon the total reactance in the circuit, but it is also affected somewhat by the point of the wave at the instant that the short circuit occurs. Therefore it is frequently a mistake to say that a certain percentage of reactance will

permit a definite current to flow on short circuit, unless one also considers the point of wave. This was brought up in a paper by Mr. A. B. Field read before this Institute.*

The question of the point of wave as well as that of the saturation in the circuit brings up the question: What is the effective internal reactance on short circuit? It is evidently a rather difficult matter to determine and it may be well for us in the Institute to decide upon some method of estimating what value should be considered correct. There may be other minor effects which influence this rush of current, such as leakage fields from other phases as well as the phase under consideration. It is my belief, however, that we can approach nearest to the correct value of effective reactance by measuring the reactance with the rotor removed; in the case of a star-connected stator between neutral and terminal, with delta connection with current in one leg only of the delta, and in the case of two-phase, across one of the phases. If, however, partly closed slots or equivalent thereof are employed, the effects of saturation cannot be neglected, and this makes it practically impossible to measure directly the reactance with this or other forms of construction which involve leakage paths that may saturate.

I would like to call your attention to the marked tendency that is at present evidenced toward securing high internal reactance, especially in large generators. Large reactance is usually obtained by the use of as large a number of turns in the stator as possible. This may be carried so far that the most economical design is not the one that is adopted. The most economical design would be that which would give the cheapest machine insofar as the relative proportions of copper and iron are concerned. One often has the idea that the larger the number of turns (the smaller the flux) the cheaper will be the machine. This is not necessarily so. In these machines it may be necessary, in order to increase the reactance by increasing the number of turns, to increase the cost. It is at times essential to use very deep slots and to laminate the conductors very carefully in order to prevent large eddy current losses.

Let us consider what are the leakage fields in the generator which are effective as reactance, it being understood that the reactance is that quantity which if divided into the electromotive force will give the current which will flow, the effect of resistance being negligible. These leakage fluxes are those which cross the slots, those which pass from tooth to tooth through the air above the slot, and those which interlink with the stator end connections. Any leakage fields from the rotor are of little or no influence. The effect of the presence of the rotor is in most generators of very small influence; any fluxes which pass from the stator through the air gap into the face of the rotor and back into the stator usually must cross the double air gap which introduces very high reluctance.

*Transactions A. I. E. E. 1912, page 1645.

When a short circuit occurs on the alternator the tendency of the armature reaction is to wipe out the field. This tendency to cause the flux to die down induces in the field winding and in all other closed circuits in the rotor, electromotive forces which cause currents to flow, which in turn tend to prevent the dying down of the flux. In the case of the field circuit this current flows back through the exciter armature. There is therefore a tendency for substantially the same electromotive force to be generated in the stator conductors at the first instant after as before the short circuit occurs. The current that flows is that electromotive force divided by the reactance.

One is liable to infer, since the reactance of a machine with a large air gap is usually less than that of a machine with a smaller air gap, that this difference is due to differences in leakage fluxes which penetrate the rotor. We wish to point out that this conclusion is not correct. It is well known that the armature reaction of the machine is nearly proportional to the pole pitch and that the air gap is proportional to the armature reaction and hence to the pole pitch also. If the pole pitch is large, corresponding to a high-speed machine, the number of turns in the stator is also small, which means that the reactance is low. Hence low reactance generally accompanies large air gaps.

Mr. Woodward: Is there any circuit breaker developed which will open a circuit in 0.01 of a second? The damage is done in the first one-half cycle, and the circuit breaker would have to operate in 0.01 of a second. We can cut off that portion of the relay curve which is not selective, and reactance is a big factor in that way.

Mr. Howard: I note on Fig. 11 of Mr. Yardley's paper, that there is another circuit breaker in connection with that quick-acting circuit breaker. Does this quick-acting circuit breaker require one more, or is this merely a test condition?

Philip Torchio: I will say a word in explanation of my recommendation of insulating the windings of reactors. I do not have reference to any specific design in any way. I said, take the reactors as you build now, but on the windings put on a light insulation. I am not recommending this to provide against the rises of potential; I assume that that has been taken care of in the design; my idea is to bring up the point of having some covering as a protection against dust and foreign objects.

I consider that essential, as in stations where we put in busbars and leads separated by brick compartments, we should not connect bare coils without separation between the windings, or something to prevent accidental contact causing short circuit.

Mr. Burnham: Several years ago I conducted a number of tests similar to those described in Mr. Yardley's paper, to determine the use of reactance for protecting synchronous converters. The results of these tests seemed to point only to one solution, and that was the availability of the quick-acting cir-

cuit-breaker. The converter cannot be protected from flashing unless the first current rush is cut down. It does not make any difference what reactance you use on the alternating current side, this will flash over if it is a dead short circuit.

To obtain, the extreme condition, a converter was short-circuited immediately after being disconnected from the a-c. circuit. It took about twelve times full load current, and flashed over. The current slowed down immediately, so no damage was done.

That shows the converter will flash over regardless of what you do to the a-c. circuit. To prevent the current rising when the converter is short-circuited, reactance was tried, but it was found that a prohibitive value of reactance was necessary in order to keep the current down for a sufficient length of time for ordinary circuit breakers to act. To use an amount of reactance that would be a reasonable size, and which could be used commercially, the circuit breakers would probably have to act three times as quick as any we have now.

It might be of interest to give some of the results of the tests with reactance in circuit. Sixty per cent reactance gave 21 times full load current. Twenty-two and a half per cent reactance which is probably the maximum commercial, gives 28 times full load current. No reactance gave 33 times. With the machine running disconnected, at full speed, the normal feed, the short circuit current varied from seven to twelve times full-load current according to the winding.

When the machine was connected with the field windings, the minimum current was obtained. This looks contradictory on its face, but the effect of the reactance of the series field was much greater than the compounding effect.

The test with the non-inductive shunt equal to the resistance of the field, gave about twelve times full load current. As a plain shunt-wound machine, it gave eleven times.

All of these values are above the flashing point as given by Mr. Yardley, as being four to six times full load current.

In Mr. Yardley's paper is the statement "It follows that if the alternating current is at all times approximately proportioned to the direct current....." The latter portions of the paper are based on this assumption. I do not find this to be true. The direct current is always decidedly higher than the alternating current for the first period of the short-circuit.

I think that is shown too on some of these curves. In the first set of curves, Figs. 2 and 3, it will be noted that the direct-current is perhaps 40 or 50 per cent higher for the first six or seven cycles than it is for the following time.

It is also stated; " there was no appreciable instantaneous d-c. generator effect." The curves I have just mentioned show there is an appreciable d-c. generator effect for the six or seven cycles. The d-c. output is appreciably higher than the a-c. input. The direct current is decidedly higher at the beginning of the short circuit.

Another statement made is that, " with considerable series field and unsaturated reactance, a converter would continue to take on load owing to its approximate straight line rising voltage characteristics." An unsaturated reactance would give a greater tendency for it to bend downward, rather than to go in a straight line. This is due to the increasing proportion of the energy current to the wattless current, which bends the converter voltage out of phase with the line voltage, and reduces it in value.

Another statement is, " The drooping characteristics on overload is obtained by employing a saturating iron core reactance." I believe the reference is true, that you get greater drop if you use a reactance, that does not saturate. The smaller the reactance the flatter the regulation curve.

J. L. McK. Yardley: The first question was in regard to the possibility of building a quick acting circuit breaker which would operate in 0.01 seconds. If you will refer to Figs. 16 to 19, you will note that the time is given and that this particular circuit breaker operated within 0.015 seconds. I believe it is only a matter of closer adjustment to reduce the time to less than 0.01 second. In fact, I understand later tests show such to be the case. This breaker of Messrs. Fortescue and Mahoney is really so unusual as to deserve a paper devoted entirely or primarily to itself.

In regard to the second circuit breaker shown in Fig. 11 of the ordinary carbon break type of construction, it was desired to secure a comparison between the results obtainable with the two types of circuit breakers. Figs. 12 to 15 should be compared with Figs. 16 to 19. For convenience, only, both breakers are shown in Fig. 11.

Mr. Burnham has described some tests made upon a synchronous converter with reactance in the a-c. circuit under the condition of dead short circuit. Of course, as I have mentioned in my paper, a rotary converter will flash over under such a condition. The figures given by Mr. Burnham for the circuit delivered at the instant of short circuit are interesting and agree with the results of other tests I know of. Fortunately, however, as brought out in the paper, the condition of dead short circuit is not met with on distributing systems of the class for which I have suggested the use of reactance in the a-c. circuit to the rotary converter as a protection. Obviously, the actual operating conditions to be experienced on any system for which any sort of protection is desired must be carefully analyzed before a recommendation is made. In my use of the term " at all times " to which Mr. Burnham objects, I mean at all times which actually occur in practice on such a system as that under consideration. Perhaps my use of such a broad term is unfortunate, but I have in mind strictly commercial conditions. Nowhere in my paper do I deny the existence of a d-c. generator action in a synchronous converter when it is short circuited. What I do claim is that this thing has been a regular bugaboo in the minds of some

people, whereas in the majority of practical cases of the class of the one I have analyzed it is negligible. In the practical case the reduction in resistance of the d-c. circuit is not either sudden enough or great enough for the rotating element of the machine to give up appreciable power, whereas reactance in the a-c. circuit is actually a protection against excessive power coming from the supply line at such a time.

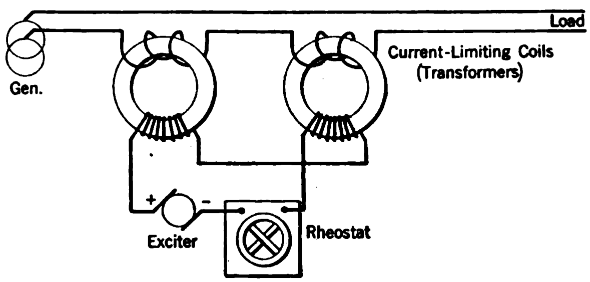
I don't exactly understand Mr. Burnham's objections to other parts of the paper. I believe it is common knowledge that the voltage regulation of a shunt-wound converter is better if the reactance in this a-c. circuit saturates as the load increases, than if it does not saturate, and that the reverse is true in the case of the compound-wound converter, the series field of which has not been too heavily shunted.

Before finishing, I desire to call attention to what seems to me the most obvious conclusions to be derived from the tests I have described. I think they point to one particular combination of a resistor, a reactor and a quick acting circuit breaker which could be applied as a protection to both service and apparatus for the case of sudden excessive overloads equally well in any one of the three classes of synchronous converter installations. I refer to such a combination located in the d-c. circuit from the converter in which the resistor and quick acting circuit breaker are in parallel electrical relationship with one another and in series relationship with the reactor. By properly varying the amounts of resistance and reactance, and also the amount of electrostatic capacity in the condenser operating the tripping device of the quick acting circuit breaker, any predetermined sudden overload may be protected against. I have already recommended such equipment for one or two installations of converters where flashovers have occurred due to sudden excessive overloads or short circuits; but so far as I know this arrangement has, as yet, not been given a practical demonstration of its worth. It is apparent that the reactor in the d-c. circuit is no protection against an excessive overload gradually accumulated. It is further obvious that to be completely protected against an excessive overload, gradually as well as suddenly attained, a reactor must also be placed in the a-c. supply circuit. A careful analysis of the operating conditions, I believe, will always show that any desired degree of protection may be attained; but it will usually show that complete and absolute protection is not warranted or even desirable. It will show in many cases that the degree of partial protection suggested in my paper for the different classes of synchronous converter installations is a matter of economy and well worth attaining.

John B. Taylor (by letter): Protective reactors have a voltage across terminals varying from zero at no load to approximately 58 per cent of line voltage under short circuit conditions. This " drop " in the coil disturbs the voltage regulation by a greater or lesser amount depending on the power factor of the load, and under the most favorable conditions is a detriment.

Accordingly, coils without iron cores are used so that the coil-drop under usual running conditions will not be an abnormally large part of the total drop when short circuit occurs. Iron is omitted for the well-known fact that its permeability falls off with increasing magnetic flux density,—in other words it becomes saturated.

As there is no known material with magnetic characteristics reversed from those of iron, *i. e.*, increasing permeability with increasing density, the air-coil with straight line characteristics, through having uniform permeability, is preferred. It is possible, however, to arrange matters, using iron itself as core, so that the desirable reversed characteristics result. This is accomplished by having the iron core saturated independently of the alternating current circuit which the coil is to limit. If the core is completely saturated no flux change will follow the alternating current unless this has sufficient number of ampere turns to



overcome those above the saturation point in the auxiliary exciting circuit.

The accompanying diagram will make the arrangement clear. For simplicity, single phase instead of three phase circuit is shown. Two coils which are practically standard transformers are connected so that the direct current saturating circuit does not form a short-circuited secondary. These serve alternately to give the desired counter e.m.f. under overload or short circuit conditions when the direct current ampere turns are overbalanced by the alternating current ampere turns. The auxiliary saturating equipment is obviously an added complication and expense but the arrangement effectively limits current on a short circuit to a definite relatively small value without excessive drop in the series coil under normal conditions. Furthermore the current on short circuit is readily controlled by varying the current in the saturating circuit.* If the saturation circuit is opened, the load circuit is practically opened also through reduction of current to magnetizing current of the choking transformers.

H. R. Summerhayes (by letter): Referring to the arrangement No. 4 of placing a large amount of permanent reactance in

*See similar diagram and oscillograms in A. I. E. E. TRANS., Vol. XXVIII, pp. 729-731.

the a-c. circuit of shunt-wound synchronous converters in order to obtain a considerable drop in continuous voltage at overloads, tests of this arrangement are described, and oscillograph records, Figures 2 to 6 are submitted with the paper.

To my mind these oscillograph records do not show that any appreciable reduction of continuous voltage was effected by the addition of the reactance in the a-c. circuit until such a long time has elapsed that the protection is ineffective. In oscillogram Fig. 3, when the load of about 11,000 amperes is applied, this load increases from zero to 10,000 amperes in a short time; practically instantaneous as compared to the scale of the oscillograph, and the continuous voltage drops from 280 to about 175 in the same short interval of time.

The oscillograph in Fig. 4, which was taken at the same time as Fig. 3, shows that when the load is applied, the voltage across the collector rings of the synchronous converter drops rather gradually; that is, several cycles are required for this voltage to drop from about 310 to 220. It is apparent that this drop in the impressed voltage across the a-c. collector rings is due to the phase displacement shown in the diagrams Fig. 1; this phase displacement means that the armature of the synchronous converter actually drops back in space from the position of the revolving flux and this mechanical displacement requires several cycles. This slow reduction in the voltage across the a-c. collector rings, which is evidently reduced by the phase displacement caused by the increase of current through the reactance, does not correspond to the sudden drop in continuous voltage at the time of the application of the load which is apparently due entirely to IR drop in the armature and external circuit.

During the period of several cycles in which the alternating voltage across the collector rings is being reduced from 300 to 200, the continuous current and voltage remain practically constant. In fact a slight increase is shown in the current.

It is evident if the d-c. load thrown on had been of a value sufficiently great to flash-over the converter, the converter would have flashed over irrespective of the reactance in the circuit since the original value of the d-c. load lasting about a tenth of a second, was not limited by the reactance. One effect of the reactance appears to have been to increase the phase displacement and, in connection with the inertia of the armature, to start hunting. It further appears that the instantaneous value of d-c. load lasted long enough to trip a circuit breaker. The reactance undoubtedly reduces the continuous current after a period of several seconds, as from oscillograph Fig. 5, it appears that the final effect of the reactance at the end of the period of hunting was to reduce the continuous current from the initial value of 10,200 to the final value of about 9000, but the action is too slow to protect the converter from flashing over or to prevent the circuit breaker from operating.

DISCUSSION ON "THE CORONA PRODUCED BY CONTINUOUS CURRENTS," (FARWELL) NEW YORK, NOVEMBER 13, 1914, (SEE PROCEEDINGS FOR NOVEMBER, 1914.)

(Subject to final revision for the Transactions.)

L. W. Chubb: The author makes certain apologies about the paper, saying it is more of technical interest than commercial value, compared with the alternating current corona. That may be so, but I believe there is a good deal of commercial value in the study of the direct potential in connection with electrical precipitation, and our fundamental study of the electron theory and effects of ionization.

I think also the paper will stimulate a good deal of further work along this line just as the first few papers on corona stimulated a great number of papers in the alternating-current work. There is too much in the paper to grasp or remember from reading it over once, but I think it is a very good paper for our records. I cannot read it without thinking of the various explanations which there may be for all the different phenomena he finds, some new, some not entirely new, but they have a very important connection with the work that is going on.

The bowing of the two wires in the same direction is a significant condition that has been brought out; and the concentration of the corona into beads or regularly spaced brushes on the negative seems, in a way, to correspond to the negative spots in the mercury arc or gas arc—the nature, of course, is different, but there is a similarity. The glow on the positive corresponds in a way to the luminosity around an anode that is being bombarded by the electron.

A. E. Kennelly: I ask Mr. Peek if he can throw any light on the movement of one of the wires mentioned on the last page where the vibration seems to be rotary as distinguished from being simply to and fro?

P. M. Lincoln: Some years ago Mr. Peek gave a formula for the loss due to corona, and that formula contained, as one of the factors, the frequency. I asked at the time why frequency should enter into a formula for the loss due to corona. It seemed to me that if it entered into this formula properly, then if we carried it down to zero frequency we would have zero loss. This paper this evening does not seem to indicate we have zero loss at zero frequency. What is the proper relation between frequency and loss? Perhaps Mr. Peek can answer that.

Max von Recklinghausen: One of the phenomena mentioned in the paper of Mr. Farwell, reminds me of a phenomenon which appears in the mercury vapor arc, which has hardly been described, namely the appearance of luminous beads on the positive electrode. They are easiest to distinguish in the lamp shown in the sketch. We have four distinct luminosity phenomena in such a lamp, namely, (1) the disintegrating point, at the negative pole, (2) the pink negative flame, (3) the luminous column, the

most typical light phenomenon in the mercury vapor lamp, and finally (4) the pink bead phenomenon near the positive. This latter can only be seen under certain conditions of temperature and vacuum, but just this phenomenon resembles vaguely the one described by Mr. Farwell. The number of beads will change rapidly with change of conditions.

I want to say one thing regarding the corona loss. I would like it to be quite clear in our mind that economically the same plays a very small part in a direct-current power transmission line. I mention this because I think it of importance that the smallest possible impediment should be thrown in the way of the development of high-tension direct-current power transmission.

L. T. Robinson: When the papers on alternating-current corona were discussed June 27, 1913, p. 1810, the fact was brought out at the meeting that the glow started a long time before the discharge started, and that we had there a rather satisfactory means, apparently, for the measurement of the high potential. But here it appears that it is even better, that is, that this critical voltage appears to be a very sharp point, and we have the commencement of the large flow on the galvanometer a long time before the glow sets in. I simply call attention to the fact that there is a definite and sharply defined effect there which I think could be put to some useful purpose.

Selby Haar: I think it will be of great interest if Mr. Farwell will give a detailed description of the generators which he uses for producing this high voltage, and also state whether they were designed under his supervision or by commercial manufacturers, and furthermore tell us why the particular sizes which were selected were chosen.

F. W. Peek, Jr.: In selecting a conductor in transmission work it is of particular importance, from the corona standpoint, to be able to predict the voltage at which loss starts. In general the operating voltage should be at or below the fair weather *disruptive critical voltage.* This paper tonight shows, as other papers have shown, that the starting voltage depends upon the maximum of the voltage wave. If the single-phase alternating critical voltage is 100 kv. effective for a sine wave, the continuous critical voltage is 141 kv. for the same conductor arrangement. The formula for the single-phase alternating effective voltage can thus be used for direct current; it is simply necessary to multiply by $\sqrt{2}$. Watson's investigations also show this. It means that in practice about 40 per cent higher continuous voltages may be used than with single phase alternating current. Compared to three-phase alternating current, the difference is greater. (It is simply necessary to consider voltages to neutral.) This point in its favor, however, will not cause direct current to supersede alternating current in high-voltage transmission.

This one advantage for direct current is still greater in solid dielectrics, as cables. In air and oil there is very little loss

until a certain definite voltage is reached. In solid dielectrics, loss starts as soon as voltage is applied and increases approximately as the square of the applied voltage—the consequent heating reduces the strength of the insulation. There is thus a gain here for direct current. It is questionable, however, how far this may be made use of, as cables generally break down by abnormal or transient voltages, which take place in either alternating-current or direct-current circuits. One other advantage is the elimination of the large capacity current.

In my 1912 paper, I gave the results of a stroboscopic study of alternating current corona; that is, the corona was viewed through an instrument in which one could see the corona due to the positive half of the wave or due to the negative half of the wave. Photographic records were shown. It is very interesting to note that the positive corona, as shown by direct-current tests, is the same as the corona due to the positive half of the alternating current wave; and vice versa, the same effects are observed for the corona on the negative half of the wave. If that paper is referred to, it will be seen that when the wires are very smooth and the negative half of the wave is observed, the negative corona first appears as a reddish crown around the wires. Finally, after operating a short time, the corona separates into more or less evenly spaced beads along the wires. In some cases, instead of taking the bead form it takes a spiral form. The positive corona is a bluish color and fits the wire surface very closely. With points, just the opposite effect occurs. The positive corona extends away out into a brush, whereas at the negative, there appears a red hot point. This difference is evidently due to the greater stress or higher gradient at the point, where new sources of ionization occur, perhaps from the metal itself.

Mr. Farwell shows that, except for very small wires—wires smaller than one-tenth of a millimeter—the alternating-current formulas may be applied for starting voltage, temperature, pressure, etc.

Dr. Kennelly has noted the photograph of the wire rotating due to corona. The same effect is also obtained with alternating current. In fact, by referring to my 1912 paper, it will be seen that in one case the wire is made to rotate as a whole, while in another, a node is formed in the center. For this particular case it is also a frequency meter. It shows on one-half of the rotation negative corona and on the other half positive corona. It is thus rotating at the frequency of the applied voltage.

A. E. Kennelly: Does the spiraling action you mention account for it?

F. W. Peek, Jr.: I do not know. I first observed the vibration of wires due to corona several years prior to the 1912 paper. Two steel wires, each 500 feet long, were stretched between two transmission towers. The spacing was perhaps ten feet. These wires vibrated; one as a whole, and the other in three

parts or with two nodes. The period was very slow, about sixty a minute. That vibration seemed to be back and forth, perhaps on account of the long span. It started when voltage in the neighborhood of 200 kv. was applied. The vibration was imperceptible when the voltage was first applied, but the amplitude gradually increased until it seemed the wires would soon come together.

Mr. Lincoln asks why, if there is a loss on direct current, the formula for the alternating-current loss indicates zero loss at zero frequency,
thus

$$p = a\,f\,(e - e_0)^2 \qquad (1)$$

There is a loss in direct current. For the same maximum voltage the direct-current loss is perhaps in the order of one-fourth the corresponding loss at 60 cycles, but for the same effective voltages the direct-current loss is very much less. Zero frequency and direct current are not necessarily identical.

The greater part of the alternating current loss is a "per cycle" loss. There is, however, a small constant loss. The more complete equation is

$$p = a_1\,(f + k)\,(e - e_0)^2 \qquad (2)$$

Where the frequency does not vary greatly from 60 cycles, (1) is more convenient to use in practical work, (2) is used over greater range. This equation was published more completely in my paper read before the Franklin Institute* about a year ago, and it was also given in my discussion at the A. I. E. E. Cooperstown meeting. The complete formula can be found in the Journal of the Franklin Institute.

I will speak briefly of another sort of corona. High-frequency corona, low-frequency corona, and direct-current corona have been discussed and are covered by the formula for alternating current corona. There is another sort of corona—the corona transients, of single impulses. It takes energy and, therefore, a very small but definite time to start a spark or corona. For continuously applied alternating or direct-current voltages the time is, relatively, practically unlimited. When the time is limited, however, as in a transient of steep wave front, or a single impulse of short duration, much higher voltages are required to produce the same effects, or to spark the same distance than when the time is not limited. This applies not only to air, but also to oil and solid insulations. I have made such a study and find, for instance, for a given shape of impulse reaching its maximum in $\frac{1}{4{,}000{,}000}$ seconds, a certain needle gap

*High voltage Engineering, Franklin Institute, Dec. 1913. Discussion, F. W. Peek, Jr., A. I. E. E.

in air requires approximately double the 60 cycle vol tage to spark over. For the same impulse reaching its maximum in $\frac{1}{400,000}$ second, the spark voltage is 25 per cent higher than the 60-cycle voltage. The time lag has in this way been accurately measured. For continuously applied alternating or direct-current voltages the initial ionization, within reasonable limits, has no effect on the corona starting voltage. For single impulses the effect may sometimes be appreciable.

S. P. Farwell: The generators used were at hand in the E. E. Department of the University of Illinois. They have been constructed without my supervision by the manufacturing company. I acknowledged in the paper the fact that F. W. Peek was the first to record beads along the negative wire in the alternating-current corona. As has been mentioned, the investigation has opened a number of new questions and further experimental and theoretical researches are in progress in the University of Illinois. The theories so far advanced cannot account for the large variety of phenomena in the corona.

DISCUSSION ON "EFFECT OF ALTITUDE ON THE SPARK-OVER VOLTAGES OF BUSHINGS, LEADS AND INSULATORS," (PEEK) AND "INSULATOR DEPRECIATION AND EFFECT ON OPERATION" (AUSTIN), NEW YORK, DECEMBER 11, 1914. (SEE PROCEEDINGS FOR DECEMBER, 1914.)

(*Subject to final revision for the Transactions*)

Harvey L. Curtis: For many years it has been known that there may be considerable leakage over the surface of insulators. However, it is only within a comparatively short time that quantitative measurements have been made. The present investigation* was undertaken to determine the conditions under which leakage would become troublesome in the use of electrical instruments. It has been extended to cover a considerable number of insulators; and for these the effects of temperature, humidity, voltage and exposure to light were studied.

The samples of materials were obtained, whenever possible, in plates 10 cm. square by 1 cm. thick. Metal strips 1 cm. wide were clamped to this with their adjacent edges 1 cm. apart, as shown in Fig. 1. The resistance was measured between strips A and strips B. The surface resistivity is assumed to be twenty times the resistance measured. While this is not strictly true, since there is leakage over the edges as well as over the face of the specimen, yet the correction is too small to take account of in the present work. To insure good contact, tinfoil was wrapped around the metal strips and carefully pressed against the surface of the insulator along the inside edge of each strip.

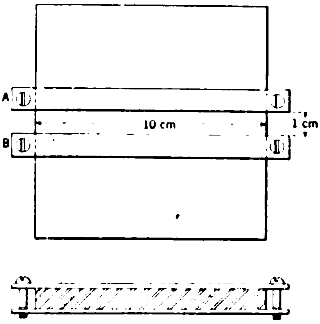


FIG. 1

To determine the effect of temperature and humidity it was necessary to place the samples in a case, the temperature and humidity of which could be maintained constant. The temperature was maintained constant by a vapor pressure thermostat. The humidity was regulated by placing in the case an open vessel containing a sulphuric acid solution of the proper strength to give the desired humidity. The air was thoroughly stirred by an eight inch fan, the driving motor being outside of the case. The leads to the specimens were brought out through blocks of paraffin on the top of the case. These were melted together, so that the case was sealed almost air-tight. A glass window permitted the reading of the temperature and humidity.

The humidity was measured by determining the temperature

*A paper, entitled, The Insulating Properties of Solid Dielectrics, has been published as Scientific Paper No. 234 of the Bureau of Standards.

at which dew would form on a polished metal surface. The deposit of dew was usually obtained by circulating cold water through a metal tube, but for very low humidities it was found necessary to use alcohol in the tube and cool it by adding carbon dioxide snow.

In measuring the resistance, high accuracy was not required. An accuracy of 10 per cent was considered sufficient. As a large number of samples were measured, and each sample measured several times, it was necessary to arrange the apparatus so that it could be worked rapidly. To do this a condenser of suitable capacity was connected in parallel with a sensitive galvanometer. The galvanometer, which had a wide range of shunts, was placed directly in the circuit with the battery and resistance to be measured. If the current was sufficient to produce a readable deflection, the galvanometer was used as an ammeter. If the current was so small that it could not be read on the galvanometer, the galvanometer only was taken out of circuit, and the current which flowed over the surface of the specimen, was collected on the condenser. After a known interval of time the galvanometer was again connected, so that the charge which had accumulated on the condenser was discharged through the galvanometer. From the time of leakage, the voltage of the battery, and the constant and deflection of the galvanometer, the resistance can be computed.

The current which flows between two conductors, maintained at different potentials and insulated from each other by a solid material, is made up of two parts; that which flows through the insulator proper, and that which flows through a film of moisture or other conducting material on the surface of the insulator. The relative importance of these will depend on the resistance of the two paths. Since water, even if very pure, conducts much better than the ordinary solid insulators, a very thin film of water may have much less resistance than the insulator.

Before discussing these further, some definitions are desirable. The volume resistivity, ρ, of a material is defined as the resistance between two opposite faces of a centimeter cube. From the relationship between the size and the resistance of a specimen it follows that

$$R = \frac{\rho l}{A} \text{ or } \rho = \frac{RA}{l}$$

where R is the resistance of a cylinder of cross section A and length l. By analogy we shall define the surface resistivity as the resistance between two opposite edges of a surface film which is one centimeter square. If the film is uniform over a surface

$$\sigma = \frac{R'b}{l}$$

where σ is the surface resistivity and R' the resistance of a rectangle of the film of length l and breadth b.

Since our measurements show that the surface film is largely moisture condensed from the surrounding atmosphere, the atmospheric humidity will largely determine the surface resistivity of a material. However, it is to be expected that the temperature of the specimen will be of some influence. Also since chemical changes are often produced by exposure to light, the surface resistivity of a material may be affected by such an exposure.

It might be expected that the applied voltage would affect the surface resistance, but, though voltages from 2 to 200 were used in some cases, no change in resistance was observed. At high humidities the resistance frequently changed by as much as a factor of 10 in the first minute after closing the key—increasing with some samples, decreasing with others. No cause for this behavior has been found. The value at the end of one minute has been taken as the correct value.

The results of our experimental work show that, for practical work in the laboratory, changes in surface leakage due to changes in temperature are of so little importance compared to the changes in resistance due to changes in relative humidity that they may be neglected. It is not to be supposed that this will hold for temperatures considerably removed from those used in this investigation; viz. 20 to 30 deg. cent.

In order to determine the effect of humidity upon the surface resistance, a number of samples were placed in the case whose temperature and humidity could be controlled. Measurements of the resistance were then made, but with an interval of at least one day after each change of humidity. After computing and tabulating the results, a curve was plotted for each sample showing its change of surface resistivity with the humidity. Nearly two hundred such curves have been plotted. From these, the curves given at the end of this discussion were selected.

Except in a few cases where it was desired to show the effect of cleaning, the samples were cleaned in the same manner and to the same extent as would be done in practical work; *i.e.*, they were wiped with a cloth or dusted with a brush.

All of the curves of surface resistivity are plotted on the same scale, so that they can be readily compared. In order to make this possible, the logarithm of the surface resistivity is plotted as ordinate, so that the actual values of the surface resistivity progress by powers of 10. In this manner very large changes of resistance can be shown on one sheet. The abscissa is the per cent of relative humidity.

Exposure to light may produce a chemical change at or near the surface. This chemical change may change the appearance of the material as well as the surface resistivity. However, there does not appear to be any connection between the two. Some samples, which show a very pronounced change

in appearance, show very little change in surface resistivity and the reverse is sometimes the case. As the chemical changes produced by sunlight take place very slowly, the number of specimens examined has been limited. The major portion of the work has been done upon hard rubber where the changes take place rather rapidly.

In Fig. 2 is a curve showing the change in surface resistance of a sample of hard rubber which was exposed to sunlight. In July 1908 the sample which had deteriorated was cleaned by washing in distilled water. This restored it to its original value, but the deterioration again proceeded rapidly.

The deterioration of some other materials when exposed to sunlight has been studied. In general it may be said that in no case is the deterioration as rapid as in the case of hard rubber. In some cases no effect has been observed.

In conclusion it may be stated that the surface leakage of

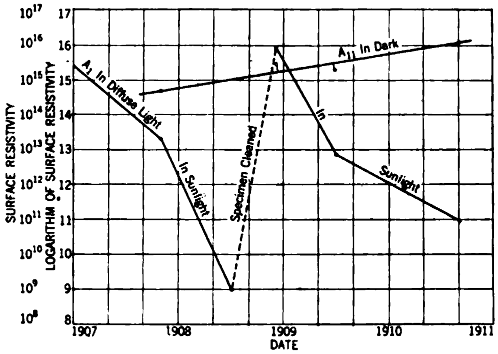


FIG. 2

the majority of materials varies greatly with the humidity of the surrounding air. This is due to the film of moisture which is condensed upon the surface. Any condition which, at a given humidity, will decrease the condensation of moisture or which will decrease the conductivity of the water will increase the surface resistance.

In Fig. 3 are given curves of four samples of hard rubber. Two had been protected from the action of the light, while two had been exposed to strong sunlight for several months. It will be noticed that between 0 and 50 per cent humidity the new rubber changes but little, while above that the changes are very pronounced. The surface resistivity is one *million* times as large at 50 per cent humidity as at 90 per cent. With the rubber which had been exposed to the light the changes in resistance continue until the lowest humidity is reached. The resistance of these specimens at very low humidity is 10^{11} times or one hundred billion times as great as is the resistance at

95 per cent humidity. It will be seen that very slight changes of the humidity will affect the insulation in a very marked manner.

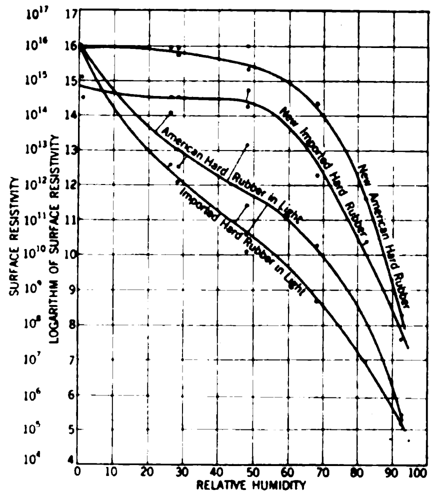


FIG. 3

Other samples of hard rubber have been tested, and those given may be taken as representative of the best grades of hard rubber. Of the two kinds whose curves are given, the imported rubber has a finer texture, and can be worked and polished

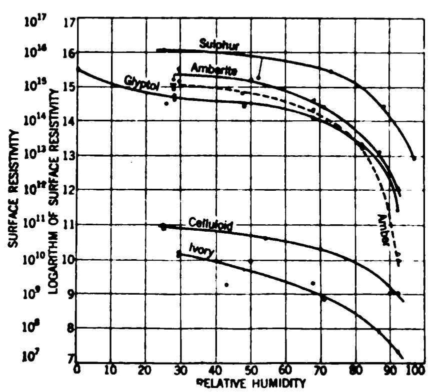


FIG. 4

better than the American rubber. However, all the tests upon the insulation show that the American rubber is the better insulator. This shows how difficult it is to connect the insulating properties with the mechanical properties.

Three of the curves given in Fig. 4 are for amber and amber-like materials. The sample of amber was a piece of clear native amber, the surface of which had been carefully polished. This is one of the few cases where only a single sample was measured. The amberite was a sample of the material which is made by compressing scrap amber. This material under the name of amberite or ambroid is now extensively used and it is apparent that so far as surface leakage is concerned it is the equal of native amber. In working with this material it was found that the specimen must be well cleaned to get the best results. Apparently handling with the fingers leaves a deposit of various deliquescent salts which condense moisture and lower the conductivity at the higher humidities. The glyptol is an artificial resin furnished by the research department of the General Electric Co. It resembles amber.

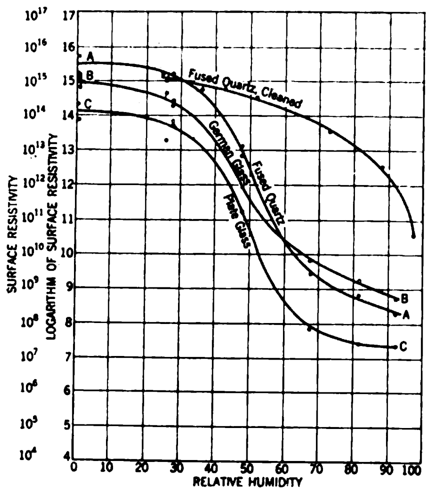


FIG. 5

Three different samples of sulphur were tested. They showed wide variations. The curve which is given lay between those of the other samples. Threlfall states that sulphur heated just to its melting point and then cooled has better insulating properties than that which has been heated to a higher temperature before cooling. The sample of celluloid was a piece of clear celluloid. Several samples were tested having various amounts of coloring matter and filler, but the surface resistivity was substantially the same for all. Ivory can not be considered as a material having high insulating properties. A substitute, white galalith, is somewhat better.

In Fig. 5 the behavior of fused quartz and certain kinds of ordinary glass is shown. Several samples of quartz were tested, but the two curves given were for the same sample. The

sample from which the curve marked "fused quartz" was obtained was cleaned in the same manner as other samples, but no special care was taken. It was carefully cleaned in strong chromic acid, washed in distilled water, and dried before obtaining the curve marked "fused quartz, cleaned." The surface was thus well freed from foreign substances. At low humidities there was no difference in the two specimens. At higher humidities there is a large difference, amounting to as much as a factor of ten thousand. This may be due to the lack of condensation of moisture on the cleaned specimen or to the fact that the water which is condensed has a lower conductivity. Doubtless both of these causes play a part.

The statement is sometimes made that the method of manufacture of fused quartz very decidedly affects the insulating properties of the product. This has not been substantiated by the results obtained in the course of this investigation.

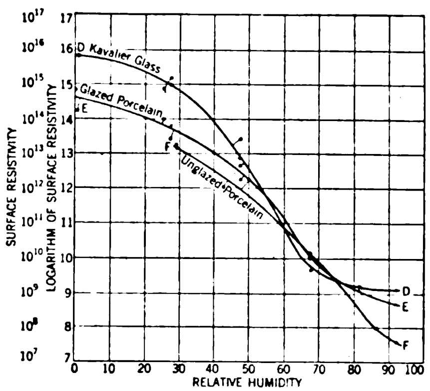


FIG. 6

A piece of old quartz tubing made by Heraeus in 1904 was measured at the same time and under the same conditions as the sample marked "quartz, cleaned." The results were practically identical. Another sample of inferior manufacture gave, under the same conditions, the same results as given by the curve marked "fused quartz."

The curves for three kinds of glass are given in Figs. 5 and 6. The Kavalier glass is a ve y hard combustion tubing having a large potassium and calcium content and a small amount of sodium. The German glass is a soft glass tubing such as is usually used in glass blowing. The plate glass was a piece from a plate-glass window. It will be noticed that the curves fall very sharply at about 30 per cent humidity, and that above 70 per cent humidity the change is not so marked. These samples were tested twice with the results as given. Later they were cleaned with chromic acid in the manner described

for quartz and the resistances measured a third time. While the results did not show such marked changes as in the case of quartz, they were all in the same direction. Also the effect was most pronounced on the hard Kavalier glass and least so on the plate glass. It is known that the Kavalier glass is less soluble* than the other forms. Hence it is quite probable that the difference may largely be due to the difference in the conductivity of the water solution on the surface.

In Fig. 6 are also given curves for glazed and unglazed porcelain. The glazed porcelain was the base of a small porcelain switch, while the unglazed was a plate such as is used in chemical work.

In Fig. 7 are grouped the curves of some of the poorer insulators, together with some curves showing the effect of impregnat-

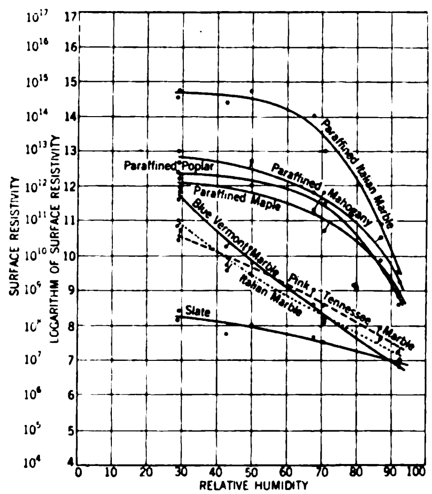


FIG. 7

ing them with paraffin. The slate was taken from the base of a switch and its origin is not known. The source of the marbles is stated on the curves. All were free from metallic veins, and were the equal of any that are used in switchboard construction. It appears that the coloring material in the Vermont and Tennessee marbles have very little effect on the surface leakage.

The marble and the different varieties of wood were impregnated with paraffin by keeping them in molten paraffin until no more air bubbles were given off. After cooling, the wood was planed and the marble sandpapered so that the resistance was measured over a surface of wood or marble with praffin filling the pores and not over a layer of paraffin on the surface.

*Hovestadt: Jena glass, p. 333.

The woods of more open grain such as mahogany and poplar show a somewhat higher insulation than the closer grained maple.

The paraffined marble shows the considerable increase in the insulation that may be obtained by impregnating with paraffin. The surface does not present as clear and pleasing appearance as before paraffining, and it accumulates dust more readily. The marked decrease of the resistance with increasing humidity is not readily explained. One would expect that it would behave more like paraffin which shows little change.

In Fig. 8 are given curves for various waxy materials. Ceresin is refined from the mineral ozokerite. It somewhat resembles paraffin, but has a higher melting point (69 deg). An attempt was made to measure the leakage resistance of a sample at several humidities by the galvanometer method using a distance of 1 mm. between the plates. It was impossible to obtain

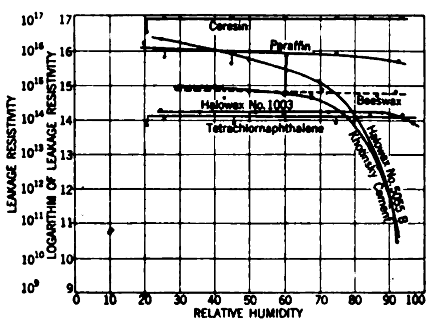


FIG. 8

a readable deflection, but it is certain the values are above those given in the curve. With the electrometer method the surface resistivity was still too high to measure, certainly above 10^{18} ohms. A special paraffin having a melting point of 58 deg. cent. also gave results too high to measure by any method at our disposal. A commercial form of paraffin known as parowax (melting point 52 deg.) gave the results shown in the curve. Measurements by the electrometer method gave a satisfactory check on these results.

The curve for beeswax was obtained from a sample of the yellow, unrefined material. White beeswax gave results which are almost identical. For these materials the surface must be fresh. They deteriorate quite rapidly when exposed to light and moisture.

The sample of tetrachlornaphthalene was furnished by Dr. Bakeland. It is doubtless a mixture of several isomers and may contain other chlorinated naphthalenes. It is about the consistency and color of yellow beeswax and has a very char-

acteristic odor. The samples of "halowax" are chlorinated naphthalenes. The sample No. 1003 is largely tetrachlornaphthalene. It is of a gray color, but in other respects has much the same properties, including odor, as the sample furnished by Dr. Bakeland. The sample 5055B is a higher chlorinated naphthalene, being largely hexachlornaphthalene.

The Khotinsky cement was flowed on a glass plate. The thickness was such that no appreciable part of the current flowed through the glass.

These waxy materials show the least change with humidity of any of the substances tested. This is doubtless due to the fact that the water does not wet the surface, hence instead of spreading over the surface is collected in minute drops.

D. B. Rushmore: In my opinion, the problem of insulator design must be solved by a scientific study of cement and a scientific study of porcelain; and by analyzing the elements, as we have in other problems, we will find out what is taking place, but the problem of measuring the causes of the trouble and knowing just what the surges are, in knowing just what the electrical forces are, and also in knowing just what are the physical conditions of the resistance opposed to these forces, is very difficult. Probably there is no other field of engineering in which it is so hard to get at these quantities with exactness.

I was very much impressed with the relation of porcelain design to the design of delicate steel castings, and it was evident in some of the insulators that have been shown on the screen that in casting these pieces of certain qualities of steel that the lines would have to be modified to prevent the undesirable forms of crystallization.

There is one thing that is closely related to the study of insulator application, and that is the practical necessity, both from an engineering and a commercial standpoint, of determining quantitatively the value of a ground wire. That has not yet been done, hundreds of thousands of dollars are spent every year in installing ground wires, and nobody knows just how much value they are, and this cannot be determined by practical experience. It must be the result of the same kind of investigation that has solved the corona problem, and that, as Mr. Curtis has shown in the method he has worked out, must be by understanding the problem of surface leakage.

E. D. Eby: These data are not only interesting, but vitally important. They affect the design and operation of all electrical apparatus, dependent upon air as an insulation. The "law of corona ".was given to us some time ago, but the probable corresponding law for spark-over has not been generally appreciated.

Since the local corona point varies directly with the density, and the spark-over voltage approximately with the density, it appears that the same relative performance will occur at all densities. Therefore, an altitude rating is logical, safe and necessary. This was found desirable by the speaker about two

years ago in connection with transformer busings, and has been applied in his practise since that time. The altitudes to be considered seldom exceed 10,000 ft. Several important installations exist at 4000 to 5000 ft.; a dividing line was set at 4000 ft., below which leads rated for 4000 ft. are supplied, and above which leads rated for 10,000 ft. are supplied.

In the cases of the leads which Mr. Peek has tested, the departure of the correction factor from δ amounts to as much as 15 per cent. of δ at $\delta = 0.50$. This would be worth considering, as it represents a fair margin between factory test voltage and spark-over. But, since 10,000 ft. is the maximum altitude reached, except in very rare instances, the departure of the correction factor from δ (6 or 7 per cent) at that altitude is not worth considering, beyond treating it as an additional margin of safety.

An interesting detail of the tests on suspension insulators is the wide departure of the correction factor from δ in the case of one unit, amounting to 44 per cent at $\delta = 0.50$ in Table IV, compared with the close agreement in the case of two, three or four-unit strings. Perhaps Mr. Peek can add some explanations to these figures.

In putting into practical application the information given in this paper, it must be remembered that these tests were made at 60 cycles, and consequently are valuable chiefly in the degree in which they represent high-frequency performance. With the usual factors of safety in the design of leads, bushings and insulators, nominal frequency voltages would seldom, if ever, tax well designed apparatus to the spark-over point of maximum elevation. It is, therefore, of primary importance that these data should apply to high frequency voltage. It is known that different designs of leads and insulators perform differently under high-frequency. Whether such differences may be expected to affect the altitude factor, perhaps Mr. Peek can tell us.

P. W. Sothman: Every time this very vital subject of insulation is touched upon, we are apt to have the feeling that we are getting further away from it, and I was afraid to-night that Mr. Austin might again change my mind in regard to certain conceptions I have had, but in many points I agree absolutely with Mr. Austin, particularly that, from a mere investigating standpoint, we should learn how to build an insulator. We have tried to teach and preach for the last few years that the insulator is one of the most important elements in the whole system; that it is as important as the generator or lightning protection, or a switch or anything else; still an insulator is chosen, because it will do a certain thing in a certain district, and it is assumed that it will do the same thing in another district, but, as Mr. Peek has pointed out, what it will do in New York it will not do in Denver.

In that respect I was very much pleased to see that Mr. Peek found a way of expressing to us here tonight, that the actual, difference in altitude has an important effect on the insulator and I think that anybody who has gone through Mr. Peek's

paper will see, as short as the paper is, and although it has been condensed to a very great degree, that the data given in it mean an immense amount of labor, and these two papers coming together this evening give us much light on the subject we are considering.

When we take the tests which have been made on insulators in the factory, and then consider the insulators which have failed out on the line, we see that we are absolutely unable to produce the same conditions, in our laboratory, no matter how we try, which agree with the conditions found in normal operation. We are trying to make high frequency tests. We test an insulator at 25,000 or 50,000 volts, and then we raise the voltage higher and higher, until the child is killed, so to speak and then we are satisfied. We think that the more power we can force through an insulator without apparent damage the better the insulator we get, but still we find in the case of insulators which will withstand a test, let us say, of 200,000 volts, in the laboratory, when we take these same insulators and put them into actual service on a line which is carrying an operating voltage of, say 50,000 volts, they will fail the next day, notwithstanding in our laboratory tests we considered them the best insulators that were ever made.

Now, gentlemen, that shows it is not the insulator, as such, that we have to blame for this condition, but there are other elements to which we must look for an explanation of this trouble. Mainly it is the line. There are a number of elements involved, and the insulator is only one of them, important, yet small. If we should build all parts of the transmission line in the way they should be built, we would see that the present factor of safety of the insulator, which is a very high one at the present time, is better than some of the other elements which are used in the transmission line.

There is one thing which is very gratifying to see, and that is that the porcelain manufacturers have actually made very great improvements in the quality of the porcelain which they produce—I would not say the insulators—but in the manufacture of porcelain they have made very great progress. When we recall how insulators stood up five years ago under what was considered at that time a very severe test, and we see how they stand up today, we conclude that we have learned, at least how to make porcelain which will serve the purpose. It is very gratifying, but I would like these gentlemen to get a little busier still, and let them try to make still further improvements; and what strikes me forcibly is that we still find that the porcelain which is imported from Europe is in many respects ahead of our porcelain which is manufactured here.

When three or four years ago we were talking about the percentage of failures—which matter Mr. Austin has referred to in a very interesting manner in his tables—we found that the failures were pretty close to forty-eight per cent, whereas today the same kind of failures amount to more nearly 6 or 7 per cent. I

think if the transmission line engineers, would cooperate with the porcelain manufacturers, and give them freely their observations, that we could still make substantial improvement in these conditions.

That brings up another point, and that has to do with these specifications for the insulator, as such. We are on the eve of determining whether we shall, or shall not make specifications for the insulators, and in that connection I cannot urge you too strongly to be very careful, and I might even caution you to go very slowly, in adopting any rule in which so many phenomena are still involved, which phenomena are so little understood by so many of our practicing engineers. There is danger that we may put into a law on this subject a great many things which may be a great handicap to the future development of the insulator.

Selby Haar: I ask Mr. Austin what is his opinion of the nature in which electrical and mechanical stresses in the strain insulator combine. Is it something like the different kinds of mechanical stresses in material, or is it something entirely different?

The reason I ask this question is that I have heard it denied in all seriousness that a strain insulator need necessarily consist of any more sections than an ordinary insulator.

Charles P. Steinmetz: We must not lose sight of the fact that, after all, the line insulator today is really in a very good condition. For many years the line insulator was the weakest link in our transmission system. It is not so today. It is rather one of the strongest links, as shown by great increase of breakdown in all other parts of the system, which formerly were protected by the line insulator failing, thus protecting the other apparatus, which is proper, because it is desirable that the line should be the last thing to break down. Breakdown in a station can be watched for, and can be located, but it is a more serious matter to have a breakdown out on a mountain peak, and then to have to hunt for it in the winter time, during snowstorms, etc.

The problem, then, is really not so much to improve the line insulator—although naturally we expect improvement—as to make sure that the insulator as it exists on the line gives as good results as possible for first-class regulation and maintenance of the insulator protection; in other words, there should be proper testing of the line insulators, and weeding out defective ones. The strains on the insulator are partly electrical strains and partly mechanical strains and that means testing them both for electrical and mechanical strains. From the electrical point of view the problem is, after all, a simpler one, for, although electrical engineering is much younger than mechanical engineering, the method of testing and the various operations are so much more accurate, that we can determine certain things with accuracy in matters electrical. Naturally, the condition of testing should be to test as nearly as possible under such conditions of electrical

stresses, etc. as breakdown the insulators on the line. We all realize that the normal line voltage and normal line frequency practically never break down the insulator, but that it is caused by very high frequency or sudden impulse, or combinations of both; and investigation shows that very often a high frequency wave train is preceded by a single still higher impulse; thus, high frequency and impulse tests are needed.

While high frequency testing has been recommended many times, it has one serious danger, namely, that most methods of producing high frequency oscillations involve the use of electrical resonance, which does not give a definite, but an indefinite, voltage and constant current effect, and it is, therefore, only a question of the power back of it whether you will break down anything or not. Therefore, while high frequency is that method of testing most nearly representing actual operating conditions, it must be made by high frequency oscillating current generators which give a definite and determinable voltage, and by the use of resonance to raise the high frequency voltage to some unknown quantity, determined by the strength of the apparatus, in which case the tests mean nothing. I refer to this latter method because it is the reason for most of the objection which has just been raised against promiscuous testing by high frequency. The proper method involves high frequency produced at definite and measurable voltage.

Not so favorable are the conditions for making the mechanical test. To some extent the mechanical quality can be determined by electrical testing. As has been pointed out in the papers a test for porosity of the porcelain can very often be determined by resistance measurements. Experience has shown, that a more reliable method in picking out mechanical defects such as flaws, porosity, etc., since it does not depend on the effect of humidity, is the use of high frequency for testing.

Unfortunately, there still remain the mechanical strains in the insulator, which may and do, as has been shown in Mr. Austin's paper, break down the insulators either immediately or through rapid deterioration, which the electrical test does not always show, and for which reliable mechanical tests have not yet been devised.

As you probably know, for some years great advantage has been derived from use of the polarscope and polarized light to test for mechanical strains glass apparatus used for electrical purposes. Sometime possibly a similar method may be developed of using light in some form or radiation by which porcelain will be made transparent—X-rays, or some similar process—and show by polarization the internal strains of the porcelain, but we do not have that at the present time.

Assuming that we have reasonably safe methods of eliminating defective insulators, there remains the depreciation to be taken care of, which is to some extent accomplished by a careful study of the design and performance of the insulator, the material of which it is made, and the method of its application.

The reliability of service given by the transmission line, as you have seen from this paper, depends upon, and can very greatly be increased by an increase of the number of units, that is, an increase of the factor of safety. The increase of reliability is greatly out of proportion to the increased margin of safety, because it is not the effect of the margin, but the probability law, which makes it much more improbable in the case of individual insulators that their strength will fall below the stress.

The second method described of increasing the reliability is to reduce the surging. The third method is to reduce the depreciation.

There is really a fourth method, which has not been referred to in the paper, and is in reality included in the last one, or reduction of depreciation, namely, weeding out insulators on the line which become defective. If there is a ten per cent depreciation in five years, by testing the insulators on the line once a year, three-quarters, say, of those which have deteriorated, can be weeded out and the average depreciation will be reduced to a small fraction of what it would have been, if all those insulators had been left in the line; this would, therefore, greatly increase the reliability of service.

That brings us to one requirement which is very badly needed, and that is reliable methods of testing the insulators on the line without taking them down; preferably, although it is not always essential, without taking the voltage off the line. Such methods would be principally valuable in high frequency tests, because while in the case of high frequency we deal with considerable power, we do not have to guard against leakage by moisture, as in resistance measurements, and it appears advisable to make systematic tests of the insulators on the transmission lines, just as such tests of underground cables, are made by testing the insulators, disk after disk, insulator after insulator, at fixed intervals, and thereby detect and weed out those which have deteriorated. This method would greatly increase the reliability of operation.

E. E. F. Creighton: Mr. Peek has again added another element to his work on corona and Mr. Austin has not only described some valuable methods but has given us a new design of insulator.

Among the several things I should like to bring up regarding Mr. Austin's paper is, first of all, the sanding of the surfaces of the insulator to give the cement a grip on them. There is a very difficult problem involved in preventing the breakage of the insulators by the cement. If this very simple method is a solution of this problem it will mean a great advance in the production of good insulators.

Many tests on the chunky insulator in Mr. Austin's illustrations show a considerable advance in the design of insulators. Even at high frequency the design is such as to overcome, to a very great extent, the creepage spark. The spark creeps down

over the upper surface of the porcelain, but has little tendency to follow the surfaces of the skirts, but jumps directly to the pin. This is an indication of better design in the insulator as it is less liable to fail.

Before closing, I want to mention the relative values of the methods of testing, among them the megger, which was used, I think, first by Mr. Gaby, in Canada. The megger gives good results where moisture can enter in the crack that is produced. If the crack does not extend all the way through the porcelain the megger is useless. If the moisture is dried out, as it usually is in pin type insulators, it is also useless. I have made tests first with the megger and then with high frequency, which showed that the megger results agreed closely with the high frequency results when moisture in the fault was present.

The direct-current test at high voltages which Mr. Austin mentions I have also used a number of times without any very great amount of success. We have gone at it with rectified currents at very high values of potential, but the trouble is that the air itself begins to leak and the current through the air is so great as to make the leakage through the insulator negligible. It is not the leakage over the surface of the porcelain because the same leakage takes place when the insulator is removed. This method of test is of value only in special studies.

The third method, which I have had occasion to speak of several times, is the use of the high-frequency transformer. No matter if the fault is due to underfired porous porcelain, or whether there is a tiny flaw somewhere in it, the high frequency will bombard the air in the internal part and will develop these flaws. At the same time the high-frequency, properly applied, is quite harmless to good porcelain. In testing porcelains the flaws are weeded out during the first few minutes, or very often in the first few seconds, and then the test can be carried on for fifty hours continuously without any more failures.

Farley Osgood: Mr. Austin brought out the fact that the value of the overhead ground wire should be considered in insulating the line, and he put that value in your minds only from the insulating and protecting standpoint.

I wish to put into your minds the fact that the overhead ground wire has a very distinct value in assisting in the locating of defective insulators, and that in forming calculations on the construction cost of transmission lines, you should take that particular point into your calculations, and not consider the value of the overhead ground wire wholly from an insulating or protecting standpoint.

Our experience leads us to believe that the overhead ground wire is worth more as an aid to the operation of the line than it is as a protective device, and by its use, with the proper test instruments behind it, faulty insulators can be located within a few spans, and sometimes exactly, which fact is especially helpful for operating companies whose practise is to test out

lines with a view of locating faults and curing the same when the lines can be relieved from actual service. The cost of an overhead ground wire of stranded steel or copper-covered steel will, in most cases, be a little more than one of the phase wires of the transmission circuit, assuming the phase wire not to be in excess of 250,000 cir. mils.

F. W. Peek, Jr.: I agree with Mr. Austin that most insulator failures occur due to small cracks in the porcelain caused by local mechanical stresses. These local stresses may be due to expansion of cement or metal parts, improper shaping of porcelain parts, etc. The so-called deterioration of porcelain is due to the gradual formation of these cracks. Electrical failure is finally the result. The following test, to show the above, may be given as an example: Six insulators all of the same porcelain, but of different designs, were tested with 60-cycle, and with oscillatory voltages. Electrically they were excellent. These insulators were then placed in ice water for one hour. This water was heated at the rate of 1 deg. a minute to the boiling point; it was then slowly cooled at the rate of 1 deg. a minute to room temperature. Cracks appeared in four insulators due to mechanical stress. Electrical failure occurred immediately upon application of voltage to these four units. The other two were not affected. They were then given a more severe test. They were put in water, which was gradually heated to the boiling point, and were then immediately plunged into ice water. One failed, while the other remained intact. These two insulators were of the best mechanical design of the lot.

Other causes of failure, due to design and manufacture, are caused by occasional impurities getting into the mixture, porous porcelain, effects of tool marks on difficult designs, etc.

In selecting an insulator it is important: (1) to see that the mechanical design is such that local mechanical stresses cannot result and gradually produce cracking; (2) to see that the electrical design is such that local electrical stress tending to produce puncture will not result; (3) to see that the porcelain is not too porous and that the product is uniform. (1) and (2) are best determined by design tests, such as the one outlined here, and others which have been described in the A. I. E. E. PROCEEDINGS.* (3) is best determined by watching the product very closely in the process of manufacture. If the per cent loss in the routine test is large, or varies greatly, the product may be looked upon as suspicious and should be condemned until the cause of the failures is found. This per cent loss will not only be a check upon the quality of the porcelain but also, to some extent, upon design. For instance, if the design is so difficult that a large percentage of failures results in its manufacture, it should be condemned. I know of insulators that have been selected on a basis of per cent loss on one of the very high-voltage lines which have given practically no trouble.

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*. A. I. E. E. PROCEEDINGS June 1913, October 1914.

So far only troubles, due to design and manufacture have been discussed. Starting with a *good insulator* operating trouble due to their improper use may result. An insufficient number of units in the case of the suspension insulator, or an insufficient "factor of safety" in the case of the pin type insulator may cause trouble. At each high over-voltage lightning impulse, or high over-voltage surge impulse, an insulator may be damaged by local cracks forming in the porcelain. A puncture is started but has not sufficient time to develop; failure will result only after a number of impulses. Most of such troubles occur on the low-voltage lines, that is, on lines operating between 20,000 and 40,000 volts. What we know as the "factor of safety" of insulators is based on operating voltages and not on lightning voltage. It is thus not really a "factor of safety," as the lightning voltage is the voltage that causes failure. I have mentioned this in former discussions, but as it is a very important point I repeat it here. Lines operating at the voltages mentioned extend out into the same sort of country and are subjected to the same electrical stresses as the higher voltage lines; as the insulators are smaller, greater damage is done. In certain parts of the country there is practically no trouble, due to this cause, when the number of insulators in a string exceeds a given number. In an exceedingly severe lightning country this number is seven to eight units. It must be realized that troubles due to this cause can only be eliminated by making the "factor of safety" on the low-voltage lines relatively higher than on the high-voltage lines.

Regarding tests there is one point I should like to make. It is unfortunate that practically all voltages differing from 60 cycles are termed "high frequency" and practically all troubles are attributed to "high frequency." An impulse, or an oscillation, or a wave of steep front, or continuous high-frequency, etc., are all given under the same heading. Naturally their effects upon insulators are quite different and there is a great deal of confusion caused. To illustrate; The puncture voltage of an ordinary insulator may be 100 kv. at 60 cycles; at high frequency of 100,000 cycles from an Alexanderson alternator this insulator will breakdown at 5 kv. due purely to heating; an oscillatory voltage such as has been referred to in one of the discussions this evening will cause puncture at about 120 kv.; a single impulse, depending upon its wave front and duration, will cause failure at anything from 100 kv. to 1000 kv. or more. This readily shows how variably these effects are, yet all are said to be caused by "high frequency." The chief criticism of all such tests so far advocated is that they are absolutely indefinite. "High frequency oscillation" testing is not a solution of the insulator problem; it is merely a means of testing, sometimes convenient, or sometimes useful as a supplement to the 60 cycle test.*

* A. I. E. E. PROCEEDINGS, June 1913, October 1914.

I have recently made some tests using single inpulses of a known wave front, length of tail, etc. Impulses with durations measured in microseconds or millionths of seconds have been used. Insulators will stand very high voltages when the duration is short. However, if the voltage is high enough some damage is done to the material. Perhaps a minute crack is formed; the effect is cumulative, and complete puncture results after a sufficient number of impulses have been applied. Such conditions actually occur on transmission lines.

E. D. Eby (by letter): In his paper on Insulator Depreciation, Mr. Austin points out that mechanical and chemical causes are chiefly responsible for insulator trouble which develops in service. Unequal temperatures in the dielectric, expansion of the cement by weathering or crystallization, and expansion of metal fittings, are mentioned as the chief causes. The paper and the discussion at the meeting dealt altogether with line insulation. I should like to ask whether in his experience Mr. Austin has encountered similar trouble with wall bushings, roof bushings or transformer bushings. It would appear that any of the causes for depreciation given might contribute to trouble with such apparatus as well as with line insulators. On the other hand, the construction of entrance and transformer bushings, particularly of filled types, is usually such that electrical weaknesses may not necessarily follow mechanical damage from cracks, etc. It would be interesting and instructive to learn the experience of manufacturing and operating companies along this line.

Edward J. Cheney (by letter): Insulator reliability becomes increasingly important as transmission distances increase and service requirements become more exacting. Such researches as that of Mr. Austin are, therefore, of the greatest interest and importance.

In one instance a large metropolitan community was absolutely dependent upon a certain transmission line. It was particularly annoying to all concerned to have the insulators on this line begin to fail with disconcerting frequency after they had given fairly good operation for several years and in spite of the fact that the lightning protection had been increased in the meantime. The remedy adopted represented the best which could be done at that time but is suggestive of brute force rather than science. It consisted in putting on new insulators having a high-potential test double that of the original ones. The results have been good so far but, in the light of the information Mr. Austin has given us, it will now be possible to examine such problems more intelligently and we can be much more confident that the remedy will be permanently effective.

H. H. Sticht (by letter): No doubt, the microscope is destined to be an important factor in the study of the insulator, just as it was in the study of iron and steel. Dr. Creighton and

Dr. Steinmetz mentioned the various methods for testing insulators, laying particular stress on the high-frequency and high-voltage tests. There is no doubt but that they are the most reliable tests that can be made in the test room, but how are they to be applied on the transmission line? If the line is one that is built through a level country they might be used. The transformers, with accessories such as a gas engine, and generator, could be mounted on a wagon and driven from tower to tower. But this can be done on very few of our transmission lines. It seems to me that in mountainous or undeveloped country, the megger-method is the only one that can be used. I will grant that the method has its limitations, but so have the other methods. Mr. Sothman called attention to the fact that you can make a high-tension test on an insulator, place it on the line, and in a day or so it will break down under operating voltage. Mr. Peek has called our attention to some interesting information regarding the effect of high-tension impulses. Have we any guarantee that a high potential test, at several times the operating voltage, does not produce a similar result on a small scale? The comparatively low voltage of the megger (1000 to 2000 volts) certainly cannot have any such bad effects. I believe that some of the bad reports about the megger have been caused by engineers trying to use it to detect faulty insulators of the "pin type." However, one can readily see that it cannot be used for this class of insulators owing to the fact that a large enough surface cannot be obtained to which to connect the megger.

H. H. Schneider (by letter): In connection with the discussion of Mr. A. O. Austin's paper on Insulator Depreciation, attention was drawn to the partially defective insulator working in the transmission line. As the elimination of this insulator is of considerable importance, a few words on this subject might be of interest.

Consider any transmission line with its thousands or tens of thousands of insulators. The continual pounding of the elements external stresses, and line surges, slowly but surely weaken the line insulators. Therefore, at any reasonable time after installation, we have in the line, insulators in every state; from the one as good as the day it was installed to the one on the verge of breaking down. Those in the latter class are of immediate concern, for although capable of withstanding normal potential, break down, when a surge or any abnormal condition arises. Of course, immediate replacing of the destroyed insulator is necessary when the break-down causes a short circuit. Interruption to service, or the loss of a feeder for an indefinite period results. Consequently, to make the transmission line as clear as is practically possible, it is incumbent upon us to systematically weed out insulators of this description by either periodic test or inspection.

I note that in attempting to weed out these partially defec-

tive insulators by means of applying overpotentials to the insulation of the line, it frequently happens that only one or two breakdowns occur upon each application. This requires the locating and the replacing of the defective insulators before the test can be further carried on. Where 15 to 25 bad insulators may be discovered in the course of a test of this nature, a great number of tests are necessary, with the result that the test drags over a considerable period. In order to expedite the test by the rapid replacing of the insulators located by test, men are generally posted along the transmission line right-of-way. Of course, a large number of men are required. Not only is this method of test far from satisfactory when a considerable number of defective insulators are on the line, but the expense connected therewith is also a heavy item. Further, where other live feeders are on the same pole as the feeder under test, the possibility that the arc will flash over to these lines when an insulator breaks down is ever present.

During the course of the discussion several gentlemen referred to the location of partially defective insulators by tests of a different nature. Mr. F. Osgood, I believe, called particular attention to their location through the medium of the ground wire. It would be of interest to have these gentlemen explain somewhat farther in this direction.

A very effective and comparatively inexpensive method of reasonably clearing a line of these insulators is by the following method of inspection. On a rainy night while the line is working under normal potential, the line should be patrolled. Partially defective insulators are readily detected by means of the arcing displayed. Close examination of the insulator can be made by means of high powered field glasses, but this is only necessary in rare cases where the period between the arcing is of considerable duration, thereby indicating that the insulator has but a slight defect or that arcing might possibly be due solely to the heavy precipitation. However, it is generally safe to treat this type of insulator as a defective insulator, for the combination of the heat produced by the arc and the rapid cooling of the insulator by the rain is gradually destroying it.

No matter how long the line, if a sufficient number of men are provided, practically all defective insulators can be noted in a single night. The number of times an inspection of this nature should be made depends entirely upon the locality and age of the line. However, three to four times a year is generally ample. Of course, no immediate change of insulators is made while the inspection is in progress, but all defective ones are noted and are replaced the next day.

R. P. Jackson (by letter): It becomes at once apparent that the whole indictment against porcelain is a secondary result of the fact that for mechanical reasons, porcelain can be used only so as to avoid subjecting it to tension. This is the reason for the use of thin sections backed up by metal in such a way as to keep the porcelain in compression or shear. The ordinary

disk suspension insulator is a good example. It is molded into a shape to fit into a head or cap of metal with a metal pin in a re-entrant recess enclosed both by the porcelain and the metal cap.

This necessarily puts the porcelain under severe electrical stress to begin with. Further, unless the cementing is perfect and the coefficients of expansion just right, there are liable to be severe mechanical strains. All efforts to reduce the electrical stress by increasing the porcelain filled space between the metal parts tends to weaken the mechanical structure of the unit by putting the porcelain under tension or bending moment.

Why not go the whole distance, however, and put the porcelain under direct tension in adequate section and thereby eliminate all trouble from puncture, by surges and lightning.

The chance of there being weak sections or units in a four piece or five piece insulator where each piece is only $\frac{5}{8}$ or $\frac{3}{4}$ in. thick is fairly high. On the other hand what lightning would puncture lengthwise 20 in. of porcelain? Regardless of the so called factor of safety, such an insulator must flash over rather than puncture.

What is the prospect of making a tougher porcelain, stronger in tension but perhaps of somewhat inferior specific dielectric strength which would deliver us from turning to the laws of chance to see how much of our equipment is really worse than worthless?

Mr. Austin shows us indeed how to make the most of the materials and methods we now have, but at best the laws of chance do not furnish a very satisfactory method of picking out defective material, of which the degree of defectiveness is progressive.

A curious result of the laws Mr. Peek has investigated is the sparking voltage of lightning arrester horn gaps at high voltages in various parts of the country.

Judging from the reports that come back from operating companies the various horn gap settings sometimes require much greater reduction and enlargement with low and high altitudes respectively than the density law would call for.

There has been a suspicion at times that some other cause such as the presence of radioactive substances in the vicinity must be necessary to account for the great horn gap settings required in certain territories. Of course, there may at times be some peculiarity of wave form which accounts for this and causes the discrepancy, but that is rather doubtful.

For example, it is our recollection that on 110,000 volts, settings of horn gaps ranging from four in. in one western locality near sea level to 15 in. in another in the mountains have been found necessary.

Has any one else data from actual operation in the Rocky Mountains as to abnormal sparking distances.?

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR FISCAL YEAR ENDING APRIL 30, 1915

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Thirty-First Annual Report, covering the fiscal year ending April 30, 1915. Detailed statements of the Institute's finances, the various trust funds, assets and liabilities, and other similar data, will be found included herein.

An examination of these statements will show that the abnormal conditions existing throughout the country during the year have not seriously affected the Institute's finances, and that the receipts for the year exceed by a considerable amount the receipts of the previous year.

A brief summary of the work accomplished during the year follows. For further details members are referred to past issues of the monthly PROCEEDINGS through the medium of which the Board endeavors to keep the membership informed regarding the administration of Institute affairs.

Meetings of the Board.—The Board of Directors has held 11 meetings during the year. Ten of these were held at Institute headquarters in New York, and one at Detroit, Mich., during the Annual Convention. An additional, adjourned meeting, was held in July 1914, for the purpose of considering the adoption of the Standardization Rules, reference to which will be found elsewhere in this report.

Following the custom of previous years, a resumé of the business transacted at these meetings has been published each month in the Institute PROCEEDINGS and in the technical press, in order that the membership may have the opportunity of keeping in touch with all matters of interest. The material published in this way, however, represents only a part of the actual business transacted by the Board, as many important matters are necessarily held over for further consideration and action, regarding which publicity is withheld pending their final settlement. All such matters are dealt with in subsequent issues of the PROCEEDINGS.

Conventions.—The Thirty-First Annual Convention was held in Detroit, Mich., June 22-26, 1914. The convention was an unqualified success in point of attendance, quality of the papers and discussions, and the enjoyment afforded by the numerous social features. The total registered attendance was 483, of which 302 were Institute members. Of the 181 guests, 100 were ladies. Fifteen technical papers were presented at the six technical sessions, the number of papers being limited to afford more time for discussion and for recreation. This arrangement met with general approval.

The Third Mid-winter Convention was held at Institute headquarters in New York, February 17-19, 1915. The program was of a general nature, the 12 technical papers presented covering a variety of subjects. The total registered attendance was 464, of which 378 were Institute members. A subscription dinner-dance was given at the Hotel Astor on the second evening, in which 350 members and guests participated.

The Sixth Annual Pacific Coast Meeting was held in Spokane, Washington, September 9-11, 1914, under the auspices of the Spokane Section, and in conjunction with the convention of the Northwest Electric Light and Power Association. The Institute contributed five of the papers presented, and the Institute's registered attendance was 192 members and guests.

Other Meetings.—An Institute meeting was held in Philadelphia, Pa., on October 12, 1914, under the auspices of the Philadelphia Section and the Committee on the Use of Electricity in Marine Work. Three papers were presented, and the attendance was about 200.

On May 28 and 29, 1914, a two day Institute meeting was held in Pittsfield, Mass., under the auspices of the Pittsfield Section. Eight papers were presented at this meeting, and the registered attendance was 177.

A two-day meeting was held in Cleveland, Ohio, on March 18 and 19, 1915, under the auspices of the Industrial Power Committee and the Cleveland Section. Six papers were presented, and the registered attendance was 309.

A two-day meeting was also held in Pittsburgh, Pa., on April 15 and 16, 1915, under the auspices of the Committee on the Use of Electricity in Mines and the Pittsburgh Section. The total registration at this meeting was 216, and seven technical papers were presented.

The increasing demand for meetings of this nature indicates a growing interest on the part of the membership which will not only greatly benefit the Institute, but will tend still further to develop its national character.

In addition to the special Institute meetings, seven meetings were held in New York. The Sections and Branches have also held their usual large number of meetings as referred to in detail in the report of the Sections Committee.

Meetings have already been authorized for next October in Philadelphia and St. Louis.

During the year President Lincoln has attended Institute and local meetings in Pittsfield, Spokane, Philadelphia, Rochester, St. Louis, Pittsburgh, Ithaca, Lynn, Chicago, Cleveland and New York.

International Electrical Congress.—In the opinion of the Executive Committee of the Committee on Organization of the International Electrical Congress, the war in Europe rendered it inexpedient to hold the Congress during the year 1915, and at a meeting held on September 25, 1914, the committee adopted resolutions recommending that the Congress be indefinitely postponed. The Board concurred in the committee's views of the situation, and on October 9 passed resolutions postponing the Congress until such time as it shall be deemed advisable to hold an International Electrical Congress in the United States. All subscriptions to the Congress were refunded in full and the Institute paid the total expense that had been incurred by the Committee on Organization of the Congress, amounting to approximately $1,500.

International Engineering Congress.—As full information regarding this Congress has been widely circulated among Institute members, it is unnecessary to go into details regarding its history and organization

in this report. The Institute continues to maintain its interest as one of the five participating societies conducting the Congress, which will be held in San Francisco, as originally planned, September 20-25, 1915. The April report of the Committee of Management shows that 2,791 members have now been enrolled on the committee's books, of which 25 per cent are foreigners, and that 139 papers have been received, a number of which are by foreign authors. The plans for this Congress are progressing favorably, and the prospects for its success are much brighter than might have been expected in view of conditions abroad.

Panama-Pacific Convention.—Recognizing that the postponement of the Electrical Congress would be disappointing to the Pacific Coast members of the Institute, and appreciating the desirability of holding a special meeting during the Exposition, the Board decided at its December meeting to authorize the Panama-Pacific Convention, to be held in San Francisco, September 16-18, 1915, during the week preceding that in which the International Engineering Congress is to be held. Information regarding the plans for the Panama-Pacific Convention may be found in the current issues of the monthly Institute PROCEEDINGS.

Honorary Vice-President on the Pacific Coast.—Believing that the prestige of the Institute would be greatly enhanced by the presence on the Pacific Coast during the Panama-Pacific exposition of a special officer or representative, the Board created at its March meeting the special office of Honorary Vice-President, and Professor Harris J. Ryan, of Leland Stanford, Jr. University, Cal., whose past services to the Institute and prominence in the engineering profession commended him as eminently qualified to represent the Institute, was unanimously chosen to fill this post of honor, unique as the first office of the kind in the Institute's history. The appointment was made effective at once and is to continue during the Exposition.

Revision of the Constitution.—Resolutions were adopted by the Board in April 1915 suggesting the appointment by the next administration of a committee to consider a revision of the Constitution, and inviting suggestions for amendments from the membership. For several years past the Institute has had such committees, and these committees have collected a large amount of data and suggestions for revision for the use of future committees. It now appears to the Board desirable that a committee be appointed at the beginning of the next administrative year to consider these and all other suggestions that may be submitted. The Board also adopted at the same meeting another resolution suggesting to the Section Delegates who attend the coming annual convention that they discuss this subject and submit such suggestions as they may decide upon.

Amendments to the By-laws.—The by-laws were amended in response to recommendations made by the Section delegates in attendance at the Detroit Convention last June. Section 55 was amended to permit the newly elected Section officers to begin their terms of office either on August 1st or on January 1st. This Section formerly provided that the terms of Section officers should coincide with that of the President of the Institute, which begins on August 1st. Section 60 was amended to incorporate the duties and functions of Section dele-

gates attending annual conventions, and to increase the amount of funds available for each Section.

Engineering Foundation.—The inauguration by the United Engineering Society on January 27, 1915, of the Engineering Foundation, to be "devoted to the advancement of the Engineering Arts and Sciences in all their branches, to the greatest good of the Engineering Profession" is one of the most important events in the annals of engineering which has occurred during the year. The Foundation, which is designed to benefit the entire engineering profession, was made possible by the generous gift, to the United Engineering Society, of $200,000, by Ambrose Swasey, of Cleveland, Ohio, to serve as the nucleus of the Foundation. The administration of the Foundation has been entrusted to a Board of eleven members composed of representatives of the four national engineering societies, the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Mining Engineers, and the American Institute of Electrical Engineers, and the United Engineering Society; also two members at large. The fund is to be held in trust by the United Engineering Society.

Employment Department.—On October 9, 1914, the Board authorized the establishment of an Employment Department at Institute headquarters, for the benefit of the Institute membership. A large number of circular letters were sent to Institute members in positions of executive and engineering responsibility, soliciting their coöperation and support, and the department has already proved helpful to employers and to members seeking employment. The plan followed, which has been described fully in the Institute PROCEEDINGS, is to publish in the PROCEEDINGS, without charge to members, brief announcements of vacancies, and abstracts of the records of available men. These announcements have increased with each monthly issue, and several members have thereby been assisted to desirable positions although the business conditions during the year have been such that the number of vacancies announced has been small compared with the number of men available. The department will doubtless prove of still greater benefit when normal business conditions are restored.

Committees and Representatives.—There has been very little change in the number and character of the standing, special, and technical committees. One new technical committee was appointed, namely, the Committee on the Use of Electricity in the Iron and Steel Industry.

The Institute has continued its representation on various joint committees and other local and national bodies with which it has been affiliated in past years all of which have been more or less active during the year.

For convenient reference, abstracts of reports submitted by the chairmen of many of the Institute committees to the Board of Directors are included herein, as follows:

Sections Committee.—The Sections and Branches have shown gratifying activity during the year, as indicated below. A new Section was organized last October in Rochester, N. Y., and application has been made for authority to organize a Section in Denver, which will be acted upon by the Board of Directors at the May meeting.

The Branches are also doing excellent work, and are steadily increasing in number, five having been organized during the year, bringing the number of Branches up to 52.

The following tabulated statement shows the activity of the Sections and Branches as compared with previous years:

	For Fiscal Year Ending						
	May 1 1909	May 1 1910	May 1 1911	May 1 1912	May 1 1913	May 1 1914	May 1 1915
Sections							
Number of Sections..	24	25	25	28	29	30	31
Number of Section meetings held.....	169	187	208	231	244	233	246
Total attendance....	16,427	16,694	15,243	19,800	22,825	22,626	23,507
Branches							
Number of Branches.	26	31	36	42	47	47	52
Number of Branch meetings held.....	198	237	255	281	357	306	328
Attendance.........	8,443	10,255	10,714	10,255	11,808	11,617	12,712

Meetings and Papers Committee.—The Meetings and Papers Committee has arranged for all of the Institute meetings and conventions held during the year, also for the Annual Convention to be held in Deer Park, Md., in June, and the Panama-Pacific Convention to be held in San Francisco in September. Arrangements are now being made for Institute meetings in Philadelphia and St. Louis in October, also for the October and November meetings in New York. All of the papers presented at the meetings have been approved by this committee, which has held monthly meetings throughout the year. In its selection and approval of the papers presented the committee has had the cooperation and assistance of the special technical committees, so that every paper offered for presentation before the Institute is reviewed by specialists in the branch of electrical engineering covered by the paper.

New York Reception Committee.—The New York Reception Committee reports a series of successful smokers which have followed the regular meetings held at Institute headquarters. The expense has been met by private subscription. The committee also made the arrangements for the successful and enjoyable dinner-dance held during the Midwinter Convention.

Standards Committee.—The Standards Committee of 1913-1914 presented its revised edition of the Standardization Rules to the Board of Directors at the Detroit Convention in June 1914. An adjourned meeting of the Board was held, on July 10, 1914, at which the Rules were approved, and the incoming Standards Committee of 1914-1915 was

authorized to make editorial revisions and to issue the new edition to take effect on December 1, 1914. The committee held meetings in October and November, at which the editorial corrections were agreed upon, and the present edition of the Rules, under date of December 1, 1914, was then issued.

Regular monthly meetings have been held by the committee during the year, at which suggested amendments to the Rules have been discussed and agreed upon. The committee intends to present a revised edition of 1915 Standardization Rules to the Board of Directors in June, to become effective in July or August, if approved. Notices of all of the committee's meetings, with a docket of matters coming up for discussion, are regularly forwarded by the committee's secretary, with a general invitation for the representatives to be in attendance, to the following bodies: Association of Railway Electrical Engineers, Society of Automobile Engineers, Illuminating Engineering Society, American Electric Railway Association, National Electric Light Association, Electrical Committee of the National Fire Protection Association, Institute of Radio Engineers, American Society of Mechanical Engineers, American Society of Civil Engineers, American Institute of Mining Engineers, American Electrochemical Society, Electric Power Club, and the American Society for Testing Materials.

Messrs. H. M. Hobart and C. E. Skinner were appointed delegates at the request of the British Rating Panel to the meetings in London, of the British Engineering Standards Committee, with the view to harmonizing the Electrical Engineering Standardization Rules in England and America. These gentlemen left New York for London on February 10, 1915, and their report was presented at the meeting of the committee held on May 7.

Code Committee.—During the past year the chairman of the Code Committee has acted as the chairman of a special committee of the National Fire Protection Association appointed for the purpose of drafting suggested changes in the elevator wiring requirements of the National Electric Code.

A very considerable amount of time has been given to assisting the United States Bureau of Standards in the preparation of a set of safety rules which the Bureau expects to issue in the near future. Several meetings have been held in Washington, D. C., and in New York, for the purpose of revising these rules.

The chairman of the Code Committee represented the Institute at the biennial meeting of the Electrical Committee of the National Fire Protection Association held in New York in March 1915. At this meeting action on Rule 13 of the National Electric Code was again deferred until the action of the National Committee on Overhead and Underground Construction was made known. This latter committee includes representatives of various associations interested in the subjects suggested in its title. The Institute has three representatives upon the committee, and its chairman is the chairman of the Institute's Code Committee.

Library Committee.—Following the custom of previous years, the Library Committee will furnish a complete report for publication in an early issue of the PROCEEDINGS.

Law Committee.—The work of the Law Committee during the year has been limited to reports on several questions of minor importance which have been submitted to it.

Railway Committee.—The Railway Committee this year has considered the electric railway standards incorporated in the Standardization Rules, and has coöperated with the Standards Committee in editing the rules relating to railway equipment. It is now coöperating with the Standards Committee in a revision of Rule No. 418, having appointed a sub-committee for that purpose which includes members of the Railway and Standards Committees.

The committee has also obtained a series of papers for the Annual Convention, dealing with the subject of contact devices for heavy traction, their cost of construction in various types, and their cost of maintenance.

Transmission Committee.—Since the last Annual Meeting this committee has prepared for final publication the comprehensive report on High Tension Transmission Practice compiled by the Engineering Data Committee of last year and offered for discussion at the Detroit Convention.

The committee provided the program for one session of the Midwinter Convention held in New York, on the general subject of high frequency testing of porcelain insulators.

The specification for the testing of high voltage porcelain line insulators, which has been in course of preparation for two years, has finally been approved by the Transmission Committee, and the Board of Directors has authorized its publication in the near future.

The committee has undertaken the collection of data on the effect of altitude on the operating temperature of electrical apparatus, but the work will not be completed for some time.

The committee is preparing a program for the Annual Convention on the subject of "Foundations for and Erection of Steel Towers for Transmission Lines."

Electric Lighting Committee.—The Electric Lighting Committee provided two papers for the March meeting in New York, and it has arranged for a joint session with the Illuminating Engineering Society at the coming Annual Convention, at which the adequate lighting of streets and systems of electrical distribution for street lighting will be considered. The committee also expects to provide papers for the Panama-Pacific Convention, or for an early meeting in New York next fall.

Industrial Power Committee.—The Industrial Power Committee laid out a program at the beginning of the year which was to include the following:

1. An effort to have at least one meeting of every Section and Branch devoted to the subject of Industrial Power.

2. To bring together within the Institute a series of illustrated lectures on Industrial Power subjects which could be kept at Institute headquarters and which would be available for the use of Sections and Branches if desired.

3. To make a complete presentation of the subject of Industrial Power applications under four general headings at four different meetings.

Three phases of the general subject have already been dealt with at the Midwinter Convention in New York, the Cleveland Meeting in

March, and the Pittsburgh Meeting in April. The fourth will be taken up at the Annual Convention.

The work of the committee for the year as a whole will have covered a large amount of ground and will have brought about the presentation of much valuable material in the Institute PROCEEDINGS. This has been due in considerable part to the early formulation of plans, to the subdivision of work among the different members of the committee, and to a coöperation on the part of all of the individual members.

Power Stations.—The Power Stations Committee has held some conferences and has collected some data, but the general feeling is that the work has not progressed to a sufficient extent to justify the presentation of a special report this year.

Electrochemical Committee.—Owing to the geographical distribution of its members, the Electrochemical Committee has not been able to hold any meetings, but has carried on its work through correspondence. The work of the committee has been confined to efforts to obtain suitable papers on electrochemical subjects. The committee arranged for the joint meeting with the New York Section of the American Electrochemical Society which was held in New York on March 12, 1915.

Electrophysics Committee.—The work of the Electrophysics Committee has been directed chiefly to the securing of papers on subjects relating to the physical theory underlying the application of electricity to electrical engineering. Six papers have thus far been considered, and a seventh is promised. Of these, two have already been presented, and three will be presented at the Annual Convention.

The New York meeting of April 9 was held under the auspices of the committee.

Iron and Steel Industry Committee.—This committee was formed with the object of promoting the use of electricity in the iron and steel industry. As the Association of Iron and Steel Electrical Engineers is organized with a similar object, and comprises within its membership practically all of the operating steel mill electrical engineers in the country, it was felt that good results might follow coöperation with the Association. Accordingly, arrangements have been made with the officers of the Association for a joint session at its coming convention to be held in Detroit, Mich., September 8-11, 1915, for which the committee will provide two papers for presentation and discussion.

Committee on the Use of Electricity in Mines.—For the last two years the efforts of the Mining Committee have been directed toward obtaining more uniform regulations for the use of electricity in mines. Up to the present time it has not been possible to obtain the coöperation necessary to effect this object, but steps have been taken to interest the U. S. Bureau of Mines, and the lead in this matter will now be taken by the Federal Government. In the near future the Institute will probably be invited to send representatives to a meeting of interested bodies to discuss this subject. The committee is making arrangements to provide papers for one session of the Panama-Pacific Convention.

Committee on Use of Electricity in Marine Work.—During the year the committee obtained several papers for presentation before the Institute, but its principal work has been directed to the collection of data from shipbuilding companies and owners, with the object of stand-

ardizing as much as possible marine installations and to have available information on good practice in such installations. As a result of the data collected, suggestions of changes in the marine section of the National Electric Code were made to the National Fire Protection Association, and three meetings of the Marine Committee have been held in conjunction with a sub-committee of the National Fire Protection Association resulting in certain desirable changes in the code being made.

Records and Appraisals of Properties Committee.—This committee has undertaken the production of a series of discussions by its members of the important features of inventories and appraisals of public service properties, with the object of bringing these discussions together into a report. The general subject has been divided into seven sub-divisions, each dealing with different phases of the subject, and each member of the committee has agreed to provide a discussion of one of these sub-divisions.

Educational Committee.—The work of the Educational Committee has consisted largely in outlining the scope of its work as distinguished from that of similar bodies. Educational work in engineering is taken care of by various bodies: and it seemed desirable to differentiate the work properly so as to avoid duplication. A list of questions was prepared covering various phases of educational work in electrical engineering, and the opinion of the members of the committee was sought upon these questions. It is hoped that the replies received will enable next year's Educational Committee to make its work more definite and systematic. Among the topics suggested are, trade and evening schools, engineering apprenticeship, research in universities, standardization of courses and of methods of instruction, etc. It is suggested that the membership of the committee in future be made more homogeneous and not so scattered geographically, in order that the committee may consider each year just one topic, and thus gradually accumulate valuable data and make definite recommendations concerning this or that phase of education in electrical engineering.

Joint Committee on Engineering Education.—This committee, constituted of representatives from several national engineering societies including the Institute, and from the Carnegie Foundation for the Advancement of Teaching, has undertaken to make a comprehensive study of engineering education. The work is progressing satisfactorily. Present methods of instruction are being determined by personal visits to representative institutions, letters of advice and of constructive criticism are being digested, and suitable tests of engineering ability to be used by schools both for entrance and for graduation are being arranged in coöperation with a psychological expert.

Editing Committee.—The Editing Committee has had general supervision over the 12 numbers of the PROCEEDINGS and the volumes of TRANSACTIONS published during its incumbency. The method of handling discussions by condensing them as much as practicable and eliminating all irrelevant matter has been continued by the present committee with satisfactory results. The amount of material published is practically the same as was published during the two previous years, and no changes in the typographical style of these publications have been found advisable.

Public Policy Committee.—The Public Policy Committee has considered a number of matters which have been referred to it during the year. Among the more important of these are the following:

Representation of the Institute at a hearing in Washington, D. C., last December, before the Senate Committee on Public Lands in relation to the Ferris Bill on the Development of Arid Lands.

With the approval of the Executive Committee, the Public Policy Committee cooperated with the Philadelphia Section last October in filing a protest against legislation to license or register engineers in the State of Pennsylvania.

Recommendations upon request of American Association for the Advancement of Science for cooperation of the Institute in an effort to reform methods of securing expert opinion in judicial procedure.

Action on communication relative to a legislative bill in connection with the inspection of buildings.

Report on advisability of making an effort to secure the appointment of an engineer as a member of the New York State Public Service Commissions.

The committee has been authorized to represent, and given power to act for, the Institute in connection with any legislation aiming to license or register engineers; also to represent the Institute in connection with the New York State Constitutional Convention.

Relations of Consulting Engineers.—This committee has directed its efforts toward the development of a schedule of fees for the use of members of the Institute practising as consulting engineers, believing that such a schedule, if approved by the Board of Directors and recognized as a proper basis for engineering fees, would tend to promote the best interests of the profession. The scope and variety of professional service rendered by members of the Institute in consulting practice are such that the committee has found the problem one of much complexity, but it hopes to present a report to the Board in time for consideration at the May directors' meeting.

U. S. National Committee, International Electrotechnical Commission. The activities of the Commission have necessarily been suspended on account of the war. No international meetings have been held during the year ending April 30, 1915, and no publications have been issued by the Central Office since No. 28, March 1914. The Honorary Secretary issued, however, a report in November 1914, in which acknowledgment was made of the action of the A. I. E. E. in helping the Central Office to carry on its work during the year on a reduced scale.

Through the successful efforts of the committee's President, Messrs. H. M. Hobart and C. E. Skinner were appointed delegates of the U. S. National Committee, and of the Standards Committee, to meetings in London, of the Rating Panel of the British Engineering Standards Committee. These gentlemen left New York on February 10, and attended several meetings of the Panel. Their report was presented at a joint meeting of the U. S. National Committee and the Standards Committee on May 7, 1915.

Edison Medal.—The sixth Edison Medal was awarded by the Edison Medal Committee, on December 29, 1914, to Dr. Alexander Graham Bell, "for Meritorious Achievement in the Invention of the Telephone."

The presentation will be made at the Annual Meeting of the Institute on May 18, 1915.

Board of Examiners.—The Board of Examiners has held 11 meetings during the year. The Board has examined and referred to the Board of Directors with its recommendations, a total of 1,695 applications of all kinds. In addition to these, the Board has reviewed a considerable number of applications a second and third time. A summary of the applications definitely disposed of is given in the following statement:

Applications for Admission.		
Recommended for election to the grade of Associate........	761	
Recommended for election to the grade of Member.........	37	
Recommended for election to the grade of Fellow..........	2	
Recommended for enrolment as students..................	798	
Not recommended for election to the grade of Member.....	15	
Not recommended for election to the grade of Fellow.......	2	1,615
Applications for Transfer.		
Recommended for transfer to the grade of Member........	48	
Recommended for transfer to the grade of Fellow...........	12	
Not recommended for transfer to the grade of Member.....	16	
Not recommended for transfer to the grade of Fellow.......	4	80
Total number of applications considered.................		1,695

The work of the Board of Examiners has increased considerably since the constitutional amendments were adopted creating three grades of membership, and providing for direct admission to any grade, and requires much more time than formerly.

Membership Committee.—The Membership Committee has been conducting an active and well-planned campaign to increase the membership, an outline of which may be found in the September 1914 PROCEEDINGS. The coöperation of the Section and Branches was also enlisted, and some of the local committees have been quite successful in producing results.

The following table shows the number of members in each grade, the total membership, and the additions and deductions that have been made during the year.

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1914.	5	439	1027	6405	7876
Additions:					
Elected................			37	714	
Transferred............		14	53		
Reinstated.............		1	5	23	
Deductions:					
Died..................		1	9	27	
Resigned..............		2	8	124	
Dropped..............		3	17	411	
Transferred............			9	58	
Membership, April 30, 1915.	5	448	1079	6522	8054

Net increase in membership during the year.................... 178

While, owing to the general business depression, the membership has not increased as much as would ordinarily have resulted from the efforts put forth, nevertheless, the membership has been kept up to a normal figure, and the results accomplished will tend to offset the losses which may be expected by reason of abnormal business conditions.

The committee also, with the sanction of the Board of Directors, extended its scope to sending communications to delinquent members with the view to retaining them on the membership list. This campaign is now under way.

Deaths.—The following deaths have occurred during the year:

Fellow.—H. Ward Leonard.

Members.—E. G. Bernard, F. P. Catchings, George Cutter, E. L. Farrar, C. E. Hansell, M. A. Marca-Romero, J. A. Sandford, Jr., H. H. Sinclair, Maurice A. Viele.

Associates.—J. A. Baylis, Alfred P. Boyd, C. F. Brackett, Guy E. Fairly, A. H. Freeman, Charles M. Gould, E. L. Haines, Edw. J. Hall, T. D. Harbinson, L. A. Hedger, J. E. Hodgson, L. H. Holtzapple, S. F. Macdonald, Kengo Makino, W. E. McWethy, H. W. Monk, Jorge Newberry, J. E. Putnam, E. A. Regestein, Stuart Richardson, A. A. Rockefeller, F. T. Rowatt, H. A. Russell, S. O. Sandell, Hugh C. Scott, B. E. Semple, T. Uweki,

Total deaths, 37.

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of the Finance Committee for the year.

New York, May 11, 1915.

Board of Directors,

American Institute of Electrical Engineers.

Gentlemen:

Your Finance Committee respectfully submits the following report for the year ending April 30, 1915.

During the past year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes and otherwise performed the duties prescribed for it in the Constitution and By-laws. Haskins & Sells, chartered accountants, have audited the Institute books, and their certification of the Institute finances follows.

In company with your Treasurer and a member of the firm of chartered accountants, the committee has examined the securities held by the Institute and finds them to be as stated in the accountants' report.

The Institute still has a liability of $54,000.00 in the form of a mortgage upon the land on which the Engineering Societies Building stands. The desirability of liquidating this mortgage has been discussed at intervals by the various Finance Committees of the past few years. In view of the present favorable financial condition of the Institute, as indicated in the accompanying statements, the present committee recommends that the Board of Directors give consideration to the cancellation of this indebtedness at an early date.

Respectfully submitted,

(Signed) J. Franklin Stevens,

Chairman, Finance Committee.

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS
30 BROAD STREET
NEW YORK

LONDON, E. C.
30 COLEMAN STREET

CHICAGO HARRIS TRUST BUILDING	ST. LOUIS THIRD NATIONAL BANK BUILDING	SAN FRANCISCO CROCKER BUILDING
CLEVELAND WILLIAMSON BUILDING	PITTSBURGH FARMERS BANK BUILDING	BALTIMORE CALVERT BUILDING

CABLE ADDRESS "HASKSELLS"

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CERTIFICATE OF AUDIT

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1915, and

WE HEREBY CERTIFY that the accompanying General Balance Sheet properly sets forth the financial condition of the Institute on April 30, 1915, that the Statement of Income and Profit & Loss for the year ended that date is correct, and that the books of the Institute are in agreement therewith.

HASKINS & SELLS
Certified Public Accountants.

NEW YORK,
May 8, 1915.

AMERICAN INSTITUTE OF

GENERAL BALANCE SHEET

EXHIBIT A.

ASSETS.

LAND AND BUILDING:			
Interest in United Engineering Society's Real Estate, No. 25 to 33 West 39th Street:			
Building		$353,346.61	
Land (One-third of Cost)		180,000.00	
Total Land and Building			$533,346.61
EQUIPMENT:			
Library—Volumes and Fixtures		$ 38,536.05	
Works of Art, Paintings, etc		3,001.35	
Office Furniture and Fixtures		10,603.61	
Total		$ 52,141.01	
Less Reserve for Depreciation		6,024.83	
Remainder—Equipment			$46,116.18
INVESTMENTS:			
BONDS:			
New York City, 4½%, 1917, Par $8,000.00		$ 8,362.50	
New York City, 4½%, 1957, Par $22,000.00		23,590.00	
City of Wilmington, Delaware, 4½%, 1934, Par $15,000.00		15,997.50	
Chicago, Burlington & Quincy Railroad Company, 4%, 1958, Par $15,000.00		14,606.25	
Total Investments			62,556.25
WORKING ASSETS:			
Publications entitled "Transactions," etc		$ 9,650.75	
Badges		934.60	
Total Working Assets			10,585.35
CURRENT ASSETS:			
Cash		$ 7,496.47	
Accounts Receivable:			
Members, for Entrance Fees and Past Dues		8,590.60	
Advertisers		1,252.75	
Miscellaneous		518.06	
Interest Accrued—Investments		831.25	
Interest Accrued—Bank Balances		94.37	
Total Current Assets			18,783.50
FUNDS:			
Land, Building, and Endowment Fund:			
Cash	$7,702.48		
Interest Accrued	79.23		
		$ 7,781.71	
Life Membership Fund:			
Cash	$5,281.39		
Interest Accrued	40.00		
		5,321.39	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$ 658.74		
New York City Bonds, 4½%, 1957, Par $2,000.00	2,268.00		
Interest Accrued	45.00		
		2,971.74	
MAILLOUX FUND:			
Cash	$ 114.05		
New York Telephone Company Bond, 4½%, 1939	1,000.00		
Interest Accrued	22.50		
		1,136.55	
Total Funds			17,211.39
Total			$688,599.28

ELECTRICAL ENGINEERS

April 30, 1915

Liabilities.

Bond and Mortgage—United Engineering Society—On Interest in Land No. 25 to 33 West 39th Street..............		$ 54 000
Current Liabilities:		
Accounts Payable—Subject to Approval by the Finance Committee..	$ 5,049.41	
Interest Accrued on Bond and Mortgage....................	720.00	
Dues Received in Advance.............................	1,150.50	
Entrance Fees and Dues Advanced by Applicants for membership..	179.50	
Total Current Liabilities........................		7,099 41
Fund Reserves:		
Land, Building, and Endowment Fund....................	$ 7,781.71	
Life Membership Fund..................................	5,321.39	
International Electrical Congress of St. Louis—Library Fund...	2,971.74	
Mailloux Fund...	1,136.55	
Total Fund Reserves..........................		17,211.39
Surplus: Per Exhibit "B"............................		610,288.48
Total......................................		$688,599.28

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STATEMENT OF CASH RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES. ALSO DISBURSEMENTS, FOR THE YEAR ENDED APRIL 30, 1915.

EXHIBIT C.

RECEIPTS AND DONATIONS:	
Land, Building and Endowment fund—Interest,	$188.94
Life Membership Fund—Interest,	192.83
International Electrical Congress of St. Louis Library Fund Donations, and Interest,	92.50
Mailloux Fund—Interest,	45.00
Total,	$519.27
DISBURSEMENTS:	
Life Membership Fund,	$343.35
Mailloux Fund,	26.75
Total,	$370.10

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past eight years.

Year ending April 30	1908	1909	1910	1911	1912	1913	1914	1915
Membership, April 30, each year	5674	6400	6681	7117	7459	7654	7876	8054
Receipts per Member	$13.01	$13.21	$13.35	$13.37	$13.19	$13.45	$14.08	$14.06
Disbursements per Member	11.73	10.49	12.03	11.03	12.44	15.57	12.86	13.54
Credit Balance per Member	$1.28	$2.72	$1.32	$2.34	$ .75	*$2.12	$1.22	$ .52

*Deficit.

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, *Secretary.*

New York, May 18, 1915.

ANNUAL CONVENTION, DEER PARK, MD.
June 29-July 2, 1915

PROCEEDINGS

OF THE

American Institute

OF

Electrical Engineers

Volume XXXIV
Number 7

JULY, 1915

Per Copy, $1.00
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Section I.—Institute Affairs

CONTENTS OF SECTION I.

Section II.—Papers, Discussions and Reports

FOR CONTENTS OF SECTION II SEE TITLE PAGE OF SECTION II

Entered as matter of the second class at the post-office, New York, N. Y., December 17, 1904, under the Act of Congress, March 3, 1879.

DEER PARK CONVENTION

June 29--July 2, 1915

This number of the PROCEEDINGS is published in advance of its regular date of issue in order to place before the membership several of the Convention papers which were received too late to be included in the June number.

The complete Convention program is published in the June PROCEEDINGS and pamphlet copies have been distributed. It is, therefore, not repeated in this number.

As we go to press there are indications that the attendance at the Deer Park Convention will be large, and an enthusiastic and enjoyable time is anticipated.

PROCEEDINGS
OF THE
American Institute
OF
Electrical Engineers.

Published monthly by the A. I. E. E.. at 33 W. 39th St., New York, under the supervision of
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GEORGE R. METCALFE, Editor

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Changes of advertising copy should reach this office by the 15th of the month, for the issue of the following month.

Vol. XXXIV **July, 1915** No. 7

Panama-Pacific Convention

The Meetings and Papers Committee of the Institute has been actively engaged for some time in preparing the technical program of the Panama-Pacific Convention and has tentatively accepted the following papers for the convention program:

Submarine Telephony and Telegraphy, by Bela Gati.
Automatic Telephone System of Los Angeles, by W. Lee Campbell.
Transient Voltages, by F. W. Peek, J·.
Arc Phenomena, by Alfred G. Collis.
Experiences with Diesel Engines Driving Generators in Mine Work, by Charles Le Grand.
Electrically Driven Compressor Plants, by L. E. Alexander.
The North Butte Hoisting Plant, by Wilfred Sykes.
Central Stations for Mine Loads, by Martin H. Gerry.
Overhead Electrolysis and Strain Insulators, by S. L. Foster.
Standard Marine Installations, by H. A. Hornor.
Commutation, by B. G. Lamme.
Delta Cross-Connections in Polyphase Systems, by G. P. Roux.
Harmonics in Transformer Magnetizing Currents, by J. F. Peters.
Train Lighting, by R. C. Lanphier.
Experimental Researches on Skin Effect in Conductors, by Messrs. Kennelly, Laws and Pierce.
Abnormal Voltages in Transformers and Type of Winding which is Immune from such Voltages, by J. Murray Weed.
Peak or Crest Voltmeters, by Clayton H. Sharp.
What Constitutes Working Capital—a symposium, collected by William B. Jackson.

There are also under consideration proposed joint sessions with the Institute of Radio Engineers and the American Electrochemical Society.

This program is not complete and is subject to change, but a complete program and most of the papers will be published in the August issue of PROCEEDINGS.

International Engineering Congress Circular of Information

A circular has recently been issued from the San Francisco headquarters of the International Engineering Congress, containing information relative to the Congress and the conventions which will be held during the week immediately preceding the Congress by the American Society of Civil Engineers, American Society of Mechanical Engineers, American Institute of Mining Engineers, and American Institute of Electrical Engineers.

The circular contains an outline of the excursions to points of engineering interest which have been arranged by the Committee of Management and which will be open to all members of the Congress and to the membership of all the societies under whose auspices the Congress has been organized.

The data given include, in addition to a brief statement regarding the en-

gineering features of these excursions, definite information relative to the cost, and the time, required for each excursion, the date and hour of starting and returning being given in each instance.

Copies of this circular may be obtained upon application to the secretaries of the societies under whose auspices the Congress has been organized, or upon application to the headquarters of the Committee of Management of the Congress, Foxcroft Building, San Francisco, Cal.

The circular also contains data regarding hotel accommodations and transportation, similar to the information contained in a circular mailed to the entire membership of the Institute and of the other societies concerned, under date of March 22, 1915.

Past Section Meetings

Boston.—May 28, 1915, Engineers Club. Addresses by Dr. Louis Bell and Mr. S. C. Rogers on "Modern Street Lighting Units." Election of officers for the coming year as follows—chairman, L. L. Elden; vice-chairman, G. A. Burnham; secretary-treasurer, Ira M. Cushing; executive committee, L. W. Abbott, William L. Puffer, and C. W. Green. Attendance 65.

Cleveland.—May 15, 1915, Akron, Ohio. Trip to Akron, Ohio, and inspection of the Gorge power house of the Northern Ohio Traction and Light Company, and the plant of the Goodyear Tire and Rubber Company, where an address was given by Mr. A. P. Lewis on "Manufacture of Automobile Tires." Election of officers as follows—chairman, E. H. Martindale; chairman of program committee, Charles S. Powell; secretary, I. H. Van Horn; executive committee, Allard Smith, H. L. Wallau and E. J. Edwards. Attendance 128.

Detroit-Ann Arbor.—May 28, 1915, Detroit Engineering Society Club Rooms. Paper: "Keokuk Development," by E. A. Lof, illustrated by lantern slides. Election of officers for the coming season as follows—chairman, Ralph Collamore; vice-chairman, A. A. Meyers; secretary-treasurer, C. E. Wise; assistant secretary-treasurer, H. S. Sheppard. Attendance 150.

Fort Wayne.—May 20, 1915, Fort Wayne Electric Works. Address by Mr. J. J. Kline on "Electric Storage Batteries." Attendance 21.

Los Angeles.—May 18, 1915, Chamber of Commerce. Paper: "Solenoid and Electromagnet Windings," by G. L. Hedges, presented by F. W. Harris. Address by Mr. R. G. Peebles on "The War in Europe." Attendance 48.

Lynn.—May 27, 1915, General Electric Works, West Lynn. Illustrated address by Mr. W. L. R. Emmet on "Ship Propulsion." Election of officers for the coming season as follows—chairman, G. N. Chamberlain; secretary-treasurer, F. S. Hall; executive committee, J. M. Davis and A. J. Cort. Attendance 202.

Minnesota.—May 10, 1915, Engineering Building, University of Minnesota. Papers: "Lake Nokomis Electric Dredge," by H. E. Brillhart, and "The Application of Electric Drive to Paper Mills, and Data Concerning the Paper Industry." Election of officers as follows—chairman, E. T. Street; secretary, W. C. Beckjord; member executive committee, F. W. Springer. Attendance 90.

Panama.—May 23, 1915, Administration Building, Balboa Heights, C. Z. Election of officers as follows—chairman, William H. Rose; vice-chairman, F. C. Clark; secretary-treasurer, C. W. Markham; executive committee, A. T. Sjoblom, E. D. Stillwell and R. H. Whitehead. Attendance 12.

Philadelphia.—May 10, 1915, Engineers Club. Papers: (1) "Load Dispatching," by James T. Lawson; (2) "Philadelphia's Newest Generating Station," by Charles Penrose. Attendance 200.

May 15, 1915, Engineers' Club. Pa-

per: "Electric Welding and Its Application," by J. H. Bryan. Joint meeting with the Engineers' Club. Attendance 90.

Pittsburgh.—May 8, 1915. Inspection trip to the Brunots Island power plant of the Duquesne Light Company. Attendance 159.

Pittsfield.—The following officers have been elected for the coming year—chairman, M. O. Troy; vice-chairman, V. E. Goodwin; secretary-treasurer, F. R. Finch; member of executive committee, N. Currie, Jr.

Rochester.—May 28, 1915. Address on "Research Work in Manufacturing Plants," by W. R. Whitney. Election of officers as follows—chairman, E. L. Wilder; secretary-treasurer, F. E. Haskell; executive committee, Scott Lynn, E. F. Davison, O. W. Bodler and E. J. Carroll. Attendance 68.

San Francisco.—May 28, 1915, Engineers' Club. Address by Prof. V. Karapetoff on "The Elements of High-Tension Insulation Design." Attendance 70.

Seattle.—May 17, 1915, Chamber of Commerce. Election of Mr. E. A. Loew as delegate to represent the Section at Annual Convention of Institute, Deer Park, Md. Discussion of Section affairs. Attendance 13.

Toledo.—June 2, 1915, Toledo Commerce Club. Address by Prof. O. W. Irwin on "Some Modern Conceptions Concerning Certain Basic Electrical Phenomena." Attendance 21.

Urbana.—May 21, 1915, Physics Building. Address by Dr. Charles T. Knipp on "Positive Rays and Allied Phenomena." Attendance 30.

Washington.—May 27, 1915, Cosmos Club Hall. Illustrated address by Mr. H. C. Eddy on "A Trip to New Zealand." Election of officers for the ensuing year as follows—chairman, Robert H. Dalgleish; secretary, Arthur Dunlop; executive committee, John H. Hanna, Myron Creese and Milan V. Ayres.

Past Branch Meetings

University of Arkansas.—May 25, 1915, Engineering Hall. Election of officers for the coming year as follows—president, P. X. Rice; secretary and treasurer, F. M. Ellington. Attendance 29.

Bucknell University.—Election of officers for the coming year as follows—president, N. J. Rehman; vice-president, S. R. Mensch; secretary-treasurer, E. C. Hageman. Attendance 9.

University of Colorado.—May 13, 1915, Hale Scientific Building. Illustrated lecture by Mr. G. D. Luther on "Storage Batteries." The following officers were elected for the coming year—chairman, Earnest F. Peterson; secretary, Samual J. Blythe. Attendance 29.

University of Kansas.—May 24, 1915, Lawrence. Election of officers as follows—chairman, E. C. Arnold; vice-chairman, V. T. Newton; secretary-treasurer, E. C. Bourke; executive committee, H. M. Stevens, A. R. Wilson, C. D. Luke, and George C. School. Attendance 26.

Lafayette College.—May 13, 1915, Pardee Hall. Papers: (1) "Submarine Signaling"; (2) "Systems of Street Lighting"; (3) "The Eastern Pennsylvania Street Railway Lines"; (4) "The Northampton Traction Company Railway." Attendance 19.

May 20, 1915. Papers: (1) "Electrical Design"; (2) "Tests on Holtzer-Cabot Machines"; (3) "The Philadelphia-Allentown Electric Railway." Attendance 18.

May 22, 1915. Papers (1) "The New York City Power Plant"; (2) "The Waterside Plant of the New York Edison Company"; (3) "Brush Losses and Testing." Attendance 18.

May 27, 1915. Papers: (1) "History and Present Status of the Arc Lamp"; (2) "Electric Power in the Textile Industry." Attendance 12.

May 29, 1915. Papers: (1) "Magnetic Properties of Electrolytic Iron

Melted in Vacuo"; (2) "Illumination at the Panama-Pacific Exposition"; (3) "The Hydroelectric Development on Bishop Creek, California"; (4) "The Mercury Vapor Rectifier." Attendance 12.

June 3, 1915. Papers: (1) "The Outdoor Substation—Its Requirements and Field of Operation"; (2) "Harrisburg, Ill., Railway and Power Plant"; (3) "Application of Small Motor Units"; (4) "Intercommunicating Telephone Systems and Their Uses." Attendance 12.

June 5, 1915. Paper: "The Electric Truck, Its Future and Advantages as Compared with the Gasoline Truck." Attendance 14.

Lehigh University.—May 17, 1915, Physical Laboratory. Address by Mr. Farley Osgood on "Engineering and the Engineer"; also "Commercial Magnetic Tests of Iron and Steel," by O. W. Eshbach. Election of officers as follows—president, A. F. Hess; vice-president, H. F. Bergstresser; secretary, R. W. Wieseman; treasurer, S. E. Heisler. Attendance 53.

Ohio State University.—May 26, 1915. Annual second semester banquet, followed by illustrated lecture by Mr. E. A. Lof on "Electrical Features of the Panama Canal." Election of officers for the coming year as follows—president, R. G. Locket; vice-president, C. F. Hanker; secretary-treasurer, D. A. Dicky. Attendance 26.

Purdue University.—April 6, 1915. Paper: "The Modern Electric Vehicle," by C. A. Jaqua. Attendance 48.

April 20, 1915. Debate on the subject of "Grounding the Neutral of a Three-Phase System," by R. C. Close and B. R. Vanleer. Attendance 14.

Rensselaer Polytechnic Institute.—May 11, 1915. Sage Laboratory. Experimental lecture on the "The Principles and Phenomena of Currents of High Voltage and High Frequency," by J. A. Terrell and J. W. Bacon. Election of officers as follows—chairman, W. J. Williams; secretary, S. N. Galvin; executive committee, T. M. Snyder, E. Hendry, W. Cravens, W. R. Townsend, J. N. Calkins, and F. M. Colvin. Attendance 75.

Rhode Island State College.—May 19, 1915. Address by Mr. Frank H. Briden on "Kinds, Uses and Manufacture of Files"; also "Electric Railroad Block Signal," by Ramon Pla. Election of officers as follows—president, Charles E. Seifert; vice-president, Phineas M. Randall; secretary, Frank A. Faron; treasurer, Thomas F. Victory. Attendance 27.

Syracuse University.—April 22, 1915. Paper: "Searchlights," by W. D. Keefer. Attendance 17.

April 29, 1915. Papers: (1) "The Development of the Incandescent Lamp," by A. D. May; (2) "Electric Welding by Low and Large Pressure Currents," by D. D. Nash. Attendance 15.

May 13, 1915. Papers: (1) "Electric Starting and Lighting Devices for Automobiles," by J. Silverman; (2) "The Electrostatic Separation of Iron Ore," by G. E. Woodard. Attendance 17.

May 20, 1915. Paper: "The Locking Caissons of the Panama Canal," by L. T. Woodruff. Attendance 13.

University of Texas.—May 28, 1915. Paper: "Transmission Line Developments in Texas," prepared by Power Transmission Committee, read by W. J. Miller. Attendance 11.

University of Washington.—May 25, 1915, Good Roads Building. Illustrated address by Mr. B. B. Bessesen on "The White Salmon Hydroelectric Development." Election of officers as follows—chairman, E. Clarence Miller; secretary, George Smith. Attendance 18.

West Virginia University.—May 14, 1915, Morgantown, W. Va. Papers: (1) "Answers to Some Questions on Electric Arc Welding"; (2) "Theoretical and Experimental Considerations of Electrical Precipitation"; (3) "The Alternating-Current Coal Hoist"; (4) "Texas' Largest Central Station"; (5) "Possibilities of Sharp Directive Wire-

less Telegraphy"; (6) "Recent Developments in Radiotelegraphy"; (7) "Protection of Telephone Circuits"; (8) "Rating of Motors." Attendance 61.

Worcester Polytechnic Institute.—May 19, 1915, Lecture Hall. Addresses as follows—(1) "The Design and Specification for a Long-Distance High-Voltage Power Transmission Line," by R. D. Hawkins; (2) "A Printing Machine for the Production of Photographs", by A. M. Vibbert; (3) "Photographic Recording of the Non-Recurrent Phenomena on the Oscillograph," by J. W. Legg. Election of officers as follows—president, R. M. Thackeray; vice-president, H. E. Whiting; secretary-treasurer, C. C. Whipple; executive committee, H. B. Smith, A. B. R. Prouty, E. L. Bragdon, and L. A. Gardner. Attendance 30.

Yale University.—May 14, 1915, Electrical Laboratory. Subject: Central Stations. Afternoon and evening meetings. Afternoon, address by Mr. V. E. Bird on "Rates." Evening was devoted to discussion on "Industrial Heating by Central Station Power," Mr. A. J. Campbell presiding. Election of officers for the coming year as follows—chairman, Vonder Smith; treasurer, Mr. Seacord; secretary, Mr. Large; executive committee, Prof. Scott, Mr. Winston and Mr. Hall. Attendance 120.

Personal

Mr. Edwin G. Hatch has opened an office for consulting work in the Equitable Building, New York, and will have associated with him Mr. Herschel C. Parker, for twenty-one years Professor of Physics in Columbia University. Mr. Hatch was formerly associated with Mr. Walter G. Clark, and during Mr. Clark's absence in the West since 1913, had entire charge of the New York office, including the consulting work for the Victoria Falls and Transvaal Power Company of London and South Africa. Mr. Hatch was also treasurer and manager of the Clark Electric and Manufacturing Company, being largely instrumental in developing that company's line of high-tension specialties.

Recommended for Transfer, June 17, 1915

The Board of Examiners, at its regular monthly meeting on June 17, 1915, recommended the following members of the Institute for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the Secretary.

To Grade of Fellow

Steen, Halfdan A., Electrical Engineer, New Jersey Zinc Co., Franklin, N. J.

To Grade of Member

Egan, Louis H., General Manager, Kansas City Electric Light Co., Kansas City, Mo.

Kalb, Warren C., Sales Engineer, National Carbon Co., Cleveland, O.

Kebler, Leonard, President, Ward Leonard Electric Co., Bronxville, N. Y.

Rowe, Hartley, Electrical Superintendent, Panama Canal, Balboa Heights, C. Z.

Applications for Election

Applications have been received by the Secretary from the following candidates for election to membership in the Institute. Unless otherwise indicated the applicant has applied for admission as an Associate. If the applicant has applied for direct admission to a higher grade than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the Secretary before July 31, 1915.

Berger, M., New York, N. Y.
Cavalcanti, A. F., Boston, Mass.
Connolly, W. B., Schenectady, N. Y.
Fager, F. D., Oak Park, Ill.
Feldman, I., New York, N. Y.

Gutting, L. A., Gatun, C. Z.
Hamilton, J. L. (Member), St. Louis, Mo.
Hill, H. F., Chicago, Ill.
Hubbard, H. Van S., Minneapolis, Minn.
Keyes, W. R., Winnemucca, Nev.
Lee, E. S., Schenectady, N. Y.
Mitchell, K. M., Sherman, Texas
Nims, H. E., Massena, N. Y.
Pettengill, H. J. (Member), St. Louis, Mo.
Pool, R. H., Youngstown, Ohio
Poor, W. E., Danvers, Mass.
Richmond, W. S., Detroit, Mich.
Squire, N. H., Downieville, Cal.
Tanabe, S., Schenectady, N. Y.
Thompson, R. G., Bowling Green, Mo.
Woodward, W. R. (Member), E. Pittsburgh, Pa.
Total 21.

EMPLOYMENT DEPARTMENT

NOTE: Under this heading brief announcements (not more than 50 words in length) of vacancies, and men available, will be published without charge to members. Copy should be prepared by the member concerned and should reach the Secretary's office prior to the 20th of the month. Announcements will not be repeated except upon request received after an interval of three months, during this period names and records will remain in the office reference files. All replies should be addressed to the number indicated in each case, and mailed to Institute headquarters.

The cooperation of the membership by notifying the Secretary of available positions, is particularly requested.

Vacancies

The United States Civil Service Commission announces an open competitive examination for illuminating engineer (salary $1,200), on July 7 and 8, to be held at numerous places in the United States.

This examination supersedes the examination for electrical engineer and draftsman, which was scheduled to be held June 23-24, the announcement of which was published in the Employment Department of the June PROCEEDINGS, and which has been cancelled. Those desiring this examination are referred to the previous announcement for details, and should apply at once for the circular relative to the examination (Form No. 489, issued June 1, 1915) and Form No. 1312, stating the title of the examination for which the form is desired, to the United States Civil Service Commission, Washington, D. C., or, if time does not permit, application blanks may be obtained from the Secretary of the Civil Service Board at the post office or custom house of any of the numerous places where the examination will be held.

Men Available

304. Electrical Engineer. Graduate University of Karlsruhe, Germany; native of Switzerland; age 28; married. One year's engineer course with Swiss company. Two years' experience with large American company, designing and research work on motors and generators; familiar with oscillograph tests. Desires position with opportunity for advancement.

305. Practical all-round electrician and recent technical graduate; single; age 27. Nine years' experience in electrical construction, maintenance and repair of electrical machinery; can handle men. Desires permanent position as chief electrician or assistant electrical engineer. Willing to go anywhere.

306. Electrical and Civil Engineer. Technical graduate; married; age 28. Desires position with concern manufacturing electric elevating and conveying apparatus. Has been connected with large elevator company during past three years. Three years student course of General Electric testing department. Location no object.

307. Superintendent of construction and operator; Mem. A. I. E. E. Specialist in installing and operating hydroelectric generating equipment of large capacity. Proficient in high-tension line construction and operation, all details of modern practise in transformer erection and general mill installation. Twenty years' experience.

308. Superintendent, chief draftsman or other factory executive position desired by mechanical and electrical engineer with fifteen years' experience in the development, design and manufacture of electrical specialties, instruments, etc. Has technical

education and general engineering, business and traveling training. Age 38; married.

309. Electrical Engineer. Age 29; married. Open for position of responsibility. Good technical education. Student apprenticeship experience, testing and manufacturing. Experienced in the design and construction of hydroelectric plants, transmission and distribution systems. Several years district superintendent for large operating company. Now electrical engineer for interurban railway.

310. Electrical Engineer. Age 25; desires responsible position with lighting company or consulting engineer; five years' experience in power plant, testing and illumination; capable of handling men. Assoc. A. I. E. E., Mem. I. E. S. and N. E. L. A. Available September 1.

311. Electrical Engineer. Technical graduate; age 28; married. Five years' experience designing, estimating, constructing and operating of power plants, transmission systems, power and light installations. Speaks Spanish, French and German. Desires position as office or field engineer anywhere; can accept position at once.

312. Technical graduate desires position as electrical engineer or superintendent. One year in charge of electrical department of manufacturing plant; one year electrical superintendent of plant in town of 5000 population; four years in charge of electrical department for electric light and railway company. Salary to start not first consideration.

313. Assistant Professor. Seven years' teaching and two and one-half years' practical experience. Author of design and laboratory notes. Available for school year beginning September 1, 1915.

314. Small investment and services are offered by electrical engineer (30); exceptional ability and experience. State full particulars.

315. Electrical Engineer; graduate; Mem. A. I. E. E.; married. Experienced in engineering, construction and executive work in telephone, electric light, power, wiring, and equipment. Desires permanent position, executive and managerial preferred.

Library Accessions

The following accessions have been made to the Library of the Institute, since the last acknowledgment.

Carnegie Free Library. Annual Report 26th, 1914. Braddock, Pa. 1915. (Gift of Carnegie Free Library.)

Cuarto Congreso Cientifico (1° Pan Americano) Resena General, por Eduardo Poirier. Santiago de Chile. 1915. (Gift of Congreso Cientifico.)

Havana Electric Railway, Light and Power Company. Annual Report to the stockholders for the year ended December 21, 1914, with Special Report on Consolidated Power Plant. Havana, Cuba, 1915. (Gift of Charles William Ricker.)

New Hampshire. Public Service Commission. Reports and Orders, vol. IV, 1914. Concord, N. H., 1915. (Gift of Public Service Commission.)

Resuscitation from Electric Shock, Traumatic Shock, Drowning, Asphyxiation from any cause. Ed. 2. By Charles A. Lauffer. New York, John Wiley & Sons, 1915. (Gift of Publishers.)

This little book is devoted to a description of the prone pressure method of resuscitation, which it describes in very plain language. It should be placed in the hands of all electric power plant employees, and all others liable to accidental asphyxiation. W. P. C.

Royal Society for the Encouragement of Arts. Manufactures and Commerce. List of Fellows, 1914-15. London, 1915. (Gift of Royal Society.)

Royal Society of London. Philosophical Transactions Ser. A, vol. 214. London, 1914. (Gift of E. D. Adams Fund.)

Underwriters' Laboratories. Organization, purpose and methods. 1915. (Gift of National Fire Protection Association.)

U. S. War Department. Statement showing rank, duties and addresses of the officers of the Signal Corps, U. S. Army, and list of officers who have been detailed in the Signal Corps or assigned to aviation duty. 1915. Washington, 1915. (Gift of U. S. War Department.)

Westinghouse Electric & Manufacturing Company. Annual Report, March 31, 1915. East Pittsburgh, 1915. (Exchange.)

Trade Catalogues

Cement Gun Co. New York City. The Cement Gun. 106 pp. 1914.

——Bulletin 40. Protection of structural steel on the P. R. R. Cortland Street Ferry Terminal, New York City.

——Bulletin 90. Provincial government of Ontario adopts cement gun construction at the hospital for the insane, Whitby, Ont.

——Bulletin 91. Tunnel waterproofing with cement and clay mortar, fifty feet below sea level.

——Bulletin 101. Cement Gun process of permanently repairing coke ovens.
——Kelly high pressure sand blast, description and instructions.
——Lining ditches with reinforced concrete.
Electric Storage Battery Co. Philadelphia, Pa. Bulletin 149. The "Exide" battery for marine wireless service. May 1915.
——Section LI, Ed. 3. The "Exide" battery types LX, SX and S. May 1915.
General Electric Company. Schenectady, N. Y. Bulletin 44406. GE-247 Ventilated commutating pole railway motor. May 1915.
——48303. Hand operated starting rheostats and panels for direct current motors. May 1915.
——Electric appliances for the home.
Leeds & Northrup Co. Philadelphia. Pa. Bulletin 210. Universal lamp and scale.
——Catalogue 48. Measurement of conductivity of electrolytes.
Matthews, W. N. & Bros. St. Louis, Mo. Catalog and handbook (No. 9) 1914.
Moore, S. L. & Sons. Elizabeth, N. J. Bulletin 17. Crescent oil engine. 1915.
——Bulletin 101. Crescent industrial electric motor truck. 1915.
Pyrene Manufacturing Co. New York City. Pyrene. May 1915.
Roller-Smith Co. New York City. "Auto Imps."
——"C. O. D. Indicators."
——Portable volt ammeter. May 1915.

UNITED ENGINEERING SOCIETY

Aluminum Electrical Conductors. Pittsburgh, Aluminum Company of America, n.d. (Gift of Aluminum Company of America.)
American Gas Institute. Lectures delivered at the Centenary Celebration of the First Commercial Gas Company, April 18-19, 1912. New York, n.d. (Purchase.)
American Small Arms. By E. S. Farrow. New York, 1904. (Purchase.)
Automobile Trade Directory. April 1915. New York, 1915. (Gift of Automobile Trade Directory.)
Azimuths of Celestial Bodies. Ed. 3. Washington, 1912. (Purchase.)
Bibliographie der Deutschen Zeitschriften Literatur. Band XXXV, 1914. Leipzig, 1915. (Purchase.)
Bricks and Artificial Stones of Non-plastic Materials, their Manufacture and Uses. By A. B. Searle. London, 1915. (Purchase.)
British Association of Gas Managers. Report of Proceedings of Annual Meeting, 1870-81. London, 1870-81. (Purchase.)
Carnegie Library of Pittsburgh. By-product coking, references to books and magazine articles. Pittsburgh, 1915. (Gift of Carnegie Library of Pittsburgh.)
Carnegie Steel Company. Carnegie-Schoen Steel Wheels. Ed. 8. Pittsburgh, 1915.
——Pocket Companion for Engineers, Architects, and Builders containing useful information and tables appertaining to the use of steel. Ed. 17. Pittsburgh, 1915.
——Standard Specifications. Ed. 5. Pittsburgh, 1915. (Gift of Carnegie Steel Company.)
Chemistry and Technology of Printing Inks. By N. Underwood and T. V. Sullivan. New York, 1915. (Purchase.)
Chemistry of Cyanogen Compounds. By H. E. Williams. London, 1915. (Purchase.)
Chemistry of the Oil Industries. By J. E. Southcombe, London, 1913. (Purchase.)
Cork: its origin and industrial uses. By G. E. Stecher. New York, 1914. (Purchase.)
Depreciation and Wasting Assets and their Treatment in Assessing Annual Profit and Loss. By P. D. Leake. London, 1912. (Purchase.)
Design and Construction of Steam Turbines. By H. M. Martin. London, 1913. (Purchase.)
Electric Mine Signalling Installations. By G. W. L. Paterson. London, 1914. (Purchase.)
Electrical Blue Book, Ed. 6. Chicago, 1913. (Purchase.)
Electrical Engineering in India. By J. W. Meares. Calcutta, 1914. (Purchase.)
Electricity for the Farm and Home. By Frank Koester. New York, 1913. (Purchase.)
Electro Plating and Analysis of Solutions. By H. H. Reama. New York, 1913. (Purchase.)
Die Elektrizität und die Textilindustrie. By George Obstfelder. Leipzig, 1912. (Purchase.)
Emery's Miners Manual. Ed. 2. Chicago, 1912. (Purchase.)
Engineering of Antiquity. By G. F. Zimmer. London, n.d. (Purchase.)
Fuel: Gaseous, Liquid and Solid. By J. H. Costs and E. R. Andrews. London, 1914. (Purchase.)
Gas Institute. Transactions, 1882-1884, 1886-1889. London, 1882-4, 1886-9. (Purchase.)
General Factory Accounting. By F. H. Timken. Chicago, 1914. (Purchase.)
Getting the Most Out of Business. By E. St. Elmo Lewis. New York, 1915. (Purchase.)
Great Britain. Board of Trade. Statistical Abstract for the United Kingdom, 1889-1913. 61st number. London, 1914. (Purchase.)
Great Britain. Home Office. Law relating to mines under the Coal Mines Act, 1911. London, 1914. (Purchase.)
Great Britain. Home Office. Second Report of the Departmental Committee appointed to enquire into the Ventilation of factories and workshops Part I, II. London, 1907. (Purchase.)
Hydraulics. By W. M. Wallace. London, 1914. (Purchase.)
Incorporated Gas Institute. Transactions, 1890-96, 1898-1902. London, 1890-6, 1898-1902. (Purchase.)
Incorporated Institution of Gas Engineers. Transactions. 1891-1894, 1896, 1903-1910. London, 1892-5, 1897, 1904-11. (Purchase.)

Manufacture of Organic Dyestuffs, translated from the French of André Wahl. By F. W. Atack. London, 1914. (Purchase.)
Marine Engineering (a text book). Ed. 4. By A. E. Tompkins. London, 1914. (Purchase.)
Motion Study as an Increase of National Wealth. By Frank B. Gilbreth. (Reprinted from the Annals of the American Academy of Political and Social Science, May 1915.) (Gift of author.)
New International Encyclopaedia. Ed. 2. vols. 9-12. New York, 1915. (Purchase.)
New Mining Laws of Alaska. 1913. By G. D. Emery. (Purchase.)
New York (County). Office of the Register. A Statement and Report showing the purposes of the Office and Changes and Improvements made during 1914. By J. J. Hopper. (Gift of Register.)
New York State. Constitutional Convention. Proposed Amendments 1915. Albany, 1915.
——Records. Albany, 1915. (Gift of Constitutional Convention.)
New York Times Index. vol. III, Jan.-March, 1915. New York, 1915. (Purchase.)
Organization and Management of Business Corporations. Ed. 2. By Walter C. Clephane. Kansas City, 1913. (Purchase.)
Penton's Foundry List, 1914-1915. Cleveland, 1914. (Purchase.)
Planing and Milling. By F. D. Jones. New York, 1914. (Purchase.)
Practical Gilding, Bronzing, Lacquering and Glass Embossing By Fredk. Scott-Michell. London, 1915. (Purchase.)
Preventing Losses in Factory Power Plants. By D. M. Myers. New York, 1915. (Purchase.)
Repair and Maintenance of Machinery. By T. W. Barber. London, 1895. (Purchase.)
Royal Societies Club. Rules, By-laws, List of Members. London, 1914. (Gift of Royal Societies Club.)
Rudimentary Treatise on Clocks, Watches and Bells for Public Purposes. By E. Beckett. London, 1903. (Purchase.)
Sanitary Refrigeration and Ice Making. By J. J. Cosgrove. Pittsburgh, 1914. (Purchase.)
South African Year Book, 1914. By W. H. Hosking. London, 1914. (Purchase.)
Starting and Lighting of Automobiles. By G. Harris and others. New York, 1915. (Purchase.)
Storage Batteries, list of references, 1900-1915 Compiled by George S. Maynard. New York, 1915. (Gift of author.)
Street Paving and Maintenance in European Cities. Report by H. W. Durham. N. Y. 1913. (Gift of N. Y. City Bureau of Highways.)
Structural Design of Warships. By William Hovgaard. London, 1915. (Purchase.)
Technical Dictionary. vol. II. By Deinhardt & Schloman. London, 1908. (Purchase.)
Theorie und Berechnung der Turbogebläse und Turbokompressoren. By By Otto Essich. Berlin, n.d. (Purchase.)
Tower Clock and how to make it. By E. B. Ferson. Chicago, 1903. (Purchase.)
United States Single Shot Martial Pistols. By C. W. Sawyer. Boston, 1913. (Purchase.)
Workmen's Compensation Act, 1906. Ed. 15. By W. A. Willis. London, 1915. (Purchase.)

(Gift of National Child Labor Committee.)
Child Labor Bulletin, Aug. 1914, pts. 1-2.
The Clinker and some other children. 1914.
Child workers of the nation. 1909.

OFFICERS AND BOARD OF DIRECTORS, 1914-1915

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(Term expires July 31, 1915.)

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(Term expires July 31, 1915.)
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EDWARD WESTON, 1888-9.
ELIHU THOMSON, 1889-90.
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ALEXANDER GRAHAM BELL, 1891-2.
FRANK JULIAN SPRAGUE, 1892-3.
*EDWIN J. HOUSTON, 1893-4-5.
LOUIS DUNCAN, 1895-6-7.
FRANCIS BACON CROCKER, 1897-8.
A. E. KENNELLY, 1898-1900.
CARL HERING, 1900-1.
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CHARLES F. SCOTT, 1902-3.
BION J. ARNOLD, 1903-4.
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*Deceased.

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Revised to July 1, 1915

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Revised to July 1, 1915

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Revised to July 1, 1915.

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SECTION II

PROCEEDINGS

of the

American Institute

of

Electrical Engineers

Papers, Discussions and Reports

CONTENTS OF SECTION II

PAPERS TO BE PRESENTED AT 32nd ANNUAL CONVENTION, DEER PARK, MD., JUNE 29—JULY 2, 1915

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

FOUNDATIONS FOR TRANSMISSION LINE, AND TOWER ERECTION
V—TORONTO POWER COMPANY

BY F. C. CONNERY

ABSTRACT OF PAPER

There is a broad field open for designing and construction engineers in the design and construction of transmission towers and foundations. The purpose of the paper is to present a brief explanation of the types of towers, tower foundations, etc. along with a few details of field practise used in connection with the construction of two lines of towers carrying six 190,000-cir. mil, seven-strand copper conductors between Niagara Falls and Toronto, Ontario.

The question of dispensing with massive concrete foundations for towers is dealt with, and a number of alternatives are presented for consideration.

THE following notes relate to the old and new 60,000-volt lines of the Toronto Power Company, between Niagara Falls and Toronto.

There are several types of towers and foundations used on these lines which are outlined in Figs. 1 to 5 inclusive. Figs. 6, 7, 8, 9 and 14, are reproduced from photographs showing various features of interest of certain of these towers.

Towers enumerated above, with the exception of that ot Fig. 3, are designed to carry two circuits of 190-000-cir. mil seven-strand copper cable, for 60,000-volt transmission; pin-type insulators are used. The tower of Fig. 3 is designed to carry four circuits of the same size conductor.

The writer will endeavor to give, from a practical viewpoint, a brief explanation of a few of the foundations used with the above mentioned towers.

Fig. 10, shows foundations used in connection with tower marked Fig. 1. About 100 sets of these footings have been dug up after being in use seven years, and in no instance has the galvanizing deteriorated, and the 3 by 6 by 24-in. impregnated wooden blocks, with a few exceptions, were in a fair state of preservation. These foundations were located in various kinds of soil.

In connection with the tower shown in Fig. 2, we did not use impregnated blocks, nor were any precautions taken, other than the hot-galvanizing, to prevent corrosion of the steel. Six of these towers were erected in low marshy black-muck, no resistance being encountered with borings at 40 ft.

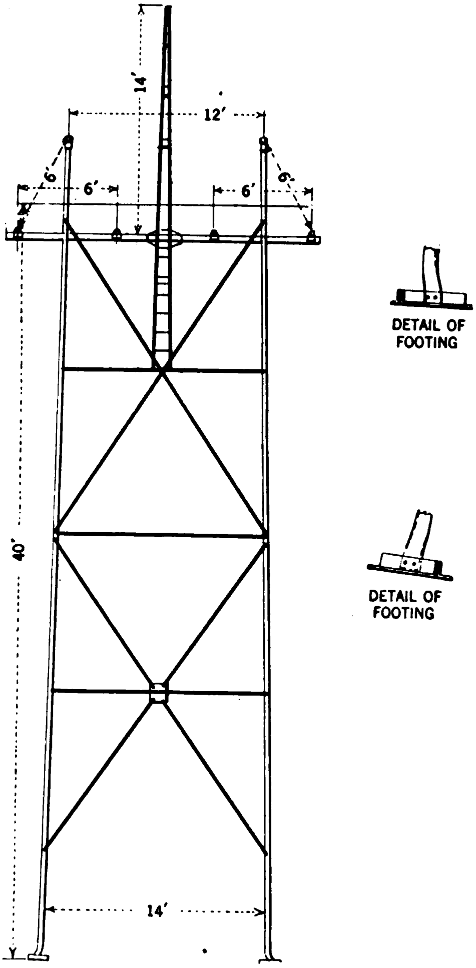


FIG. 1—STANDARD TOWER WITH GROUND SPIRE

A two-inch plank sheathing was driven around each tower-leg location, the muck dug out and a floating foundation built six feet below the ground surface; this consisted of impregnated two-inch planking, the footings being set in concrete, approximately

one yard of cement being placed around and under each stub, the excavations being 30 in. by 30 in. by 6 ft. These towers have been erected for one year and have neither settled nor gotten out of alignment.

I may say that great care was taken in connection with the locating of towers, so as to avoid, where possible, soft marshy

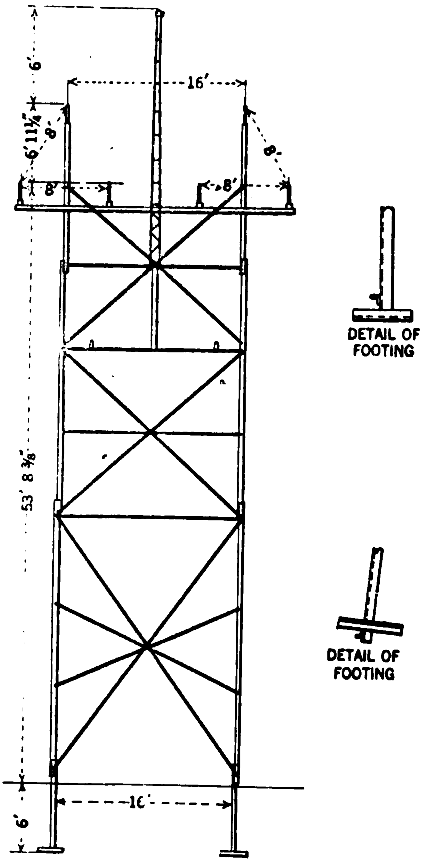


FIG. 2—STANDARD 53-FT TOWER

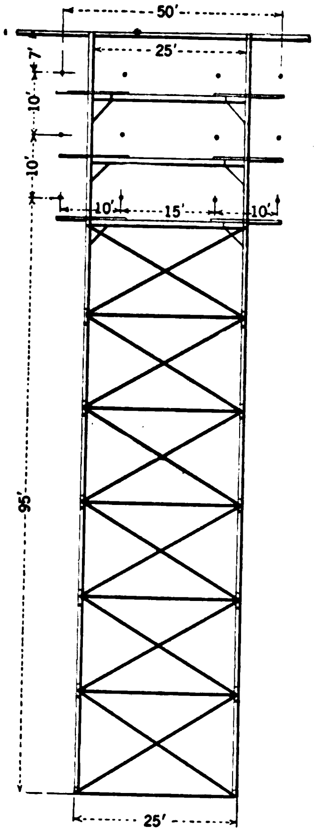


FIG. 3—FOUR-CIRCUIT LAKE TOWER

soil and also to equalize the grade. Tower footings in gravel, or a mixture of sand and loam packed tightly, offer a great resistance against upward pull.

A number of towers of the type marked Fig. 2, were erected in rock. This rock was thinly stratified and was easily excavated to a depth of three feet. The stubs were cut down to 3 ft. 6 in.,

and were concreted in with a one-to-four mixture. This construction has proved satisfactory.

In Figs. 6 to 9, are shown a type of narrow-base latticed tower. The foundations for these were built in two ways.

(a) A foundation 6 ft. by 6 ft. by 6 ft. with twelve $1\frac{1}{4}$-in. anchor

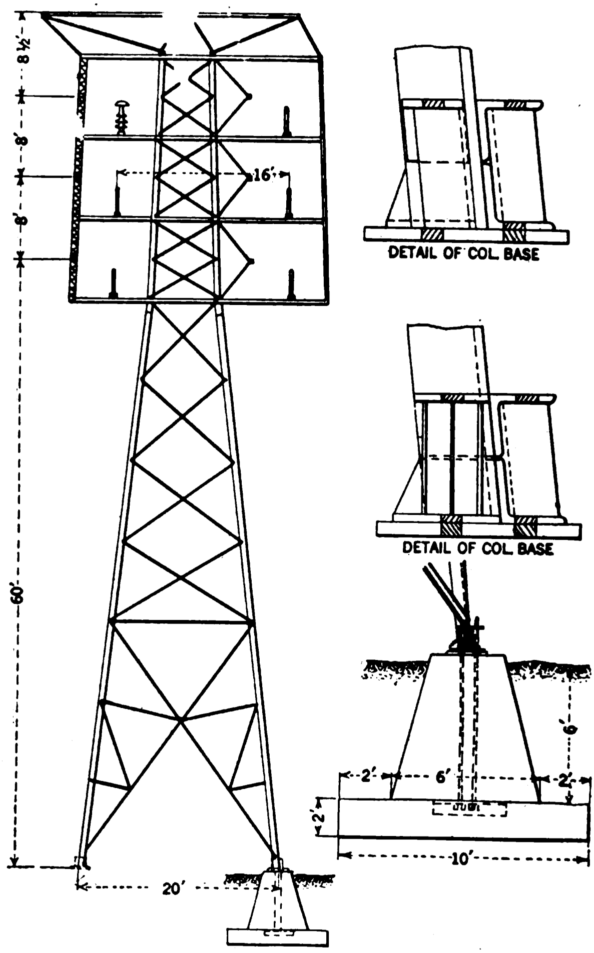
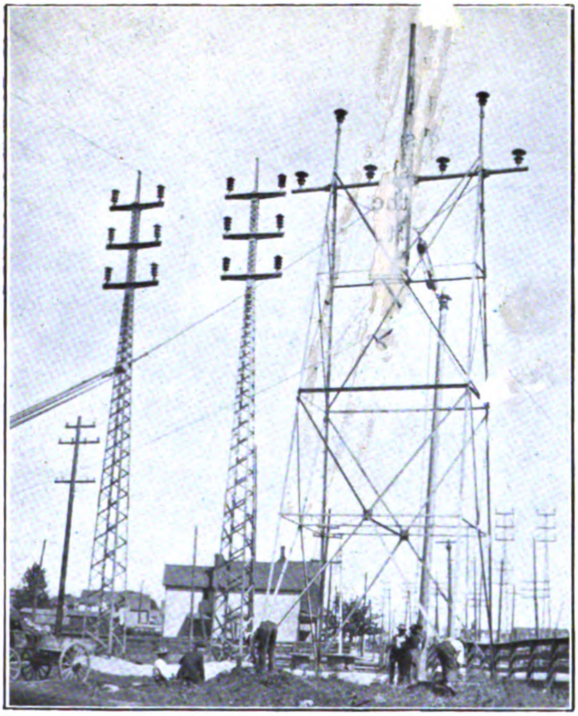


FIG. 4—ANGLE TOWER FOR ANGLES TO 60 DEGREES

bolts 5 ft. 6 in. long. This was a one-three-five concrete mixture.

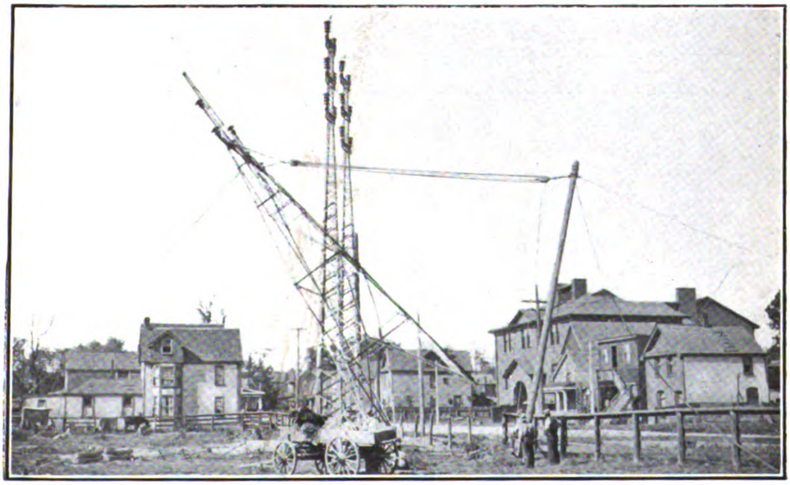
(b) Foundations 6 ft. by 6 ft. and varying in depths were built in the following manner:

Excavation was taken out, copper grounding-ribbon placed, and 12 inches of one-three-five concrete placed and tamped.



[CONNERY

FIG. 6—METHOD OF LOWERING STANDARD 40-FT. TOWER—FIRST POSITION



[CONNERY]

FIG. 7—METHOD OF LOWERING STANDARD 40-FT. TOWER—SECOND POSITION

No anchor bolts were used, but the tower was erected on this 12-in. base, and then the excavation filled with one-three-five concrete. This method being used on account of the variation in the dimension of the bases of these towers. Minimum depth 6 ft.

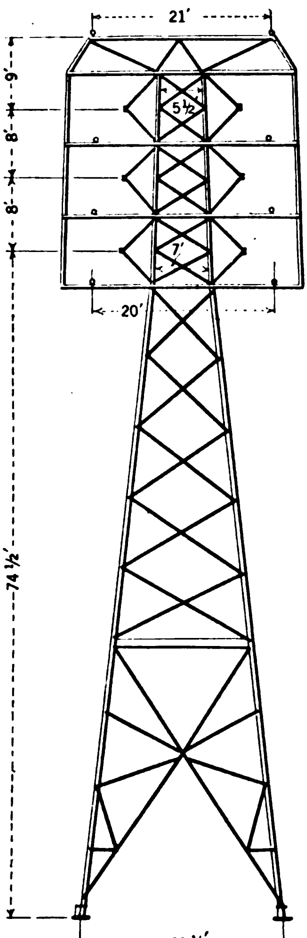


FIG. 5—HEAVY 75-FOOT STRAIN TOWER

Construction of Footing. (Fig. 3) Eleven of the above footings were constructed in the waters of Lake Ontario at Burlington Beach, Ontario, the mean depth of water being about three ft.

A double coffer-dam was built of 2 by 8-in. tongued and grooved spruce, driven to a depth of 10 feet below the lake bottom by a small steam hammer. The water was pumped out, and sand and gravel excavated to a depth of six feet below the lake bottom where very coarse gravel was encountered.

The foundations were then constructed as shown, the spruce sheeting being left in to protect against scouring. After the foundations were complete, a tallis of 10-inch rock, each piece weighing from 500 to 1500 lb. was built around the two outer footings of each foundation for extra protection, the location of these towers being on a shore where storms from the East are very prevalent.

Method of Setting Stubs. Fig. 15 shows the template used with success in the setting of stubs. This template was carried by the setting-gang, lined up on the center line stakes and levelled by the gang foreman by means of a carpenters level, and then blocked up and checked.

The stubs were bolted to the template and the filling in of holes proceeded with. One man back-filled while two men tamped. Special attention on the part of the foreman should be given to the tamping, as workmen are apt to do this in a careless manner.

Where water was available it was used to settle the back-filling.

The towers were assembled at the locations where they were to be erected, and were erected with a shear-leg outfit. From eight to twelve towers of the type marked Fig. 2 were erected in one day by eight men and one team.

The writer has used portable derricks, gin-poles, etc. for erecting towers, and can say that the shear-leg method is the most efficient, except where cramped for room, when the gin-pole should be used.

The shear-legs used, were constructed in the following manner: two pieces of 6-in. by 8-in. clear Georgia-pine, 34 ft. long were bolted together with a 1-in. by 14-in. through bolt, 14 inches from the top. This along with a set of 12-in. triple blocks, hand-lines,

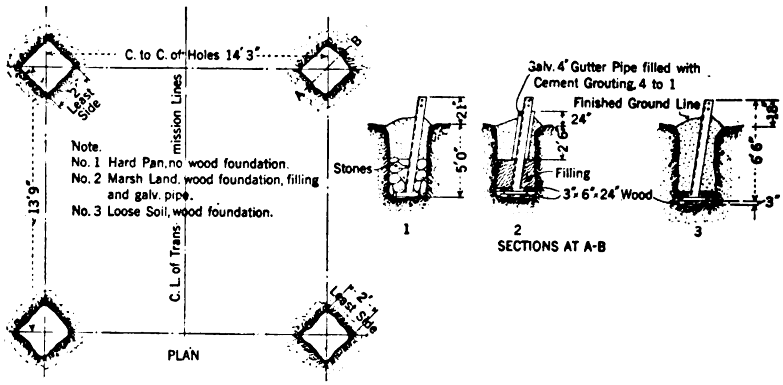
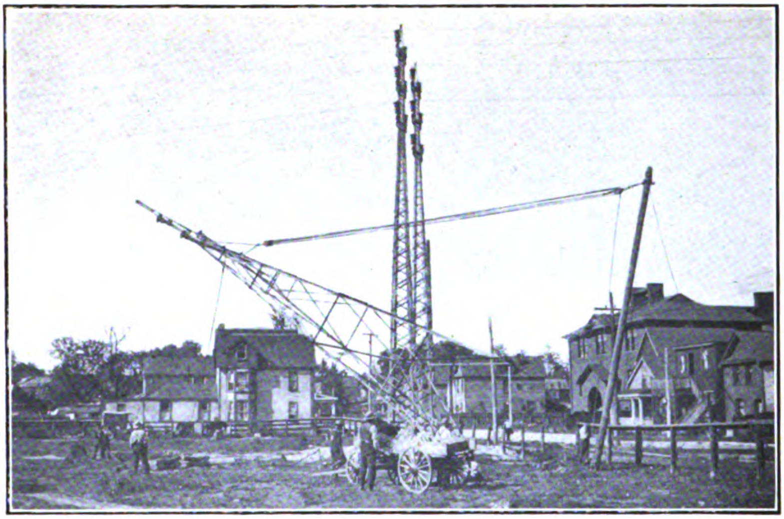


FIG. 10—DIAGRAMS OF STANDARD 40 FOOT TOWER—FOUNDATIONS IN DIFFERENT SOILS

anchor-pins, etc., makes a cheap and serviceable erecting outfit. The above outfit was used in the erection of a line of 928 towers averaging $2\frac{1}{4}$ tons each, and only one mishap occurred, this being caused by negligence on the part of the foreman in charge, and was in connection with the first tower erected on the line.

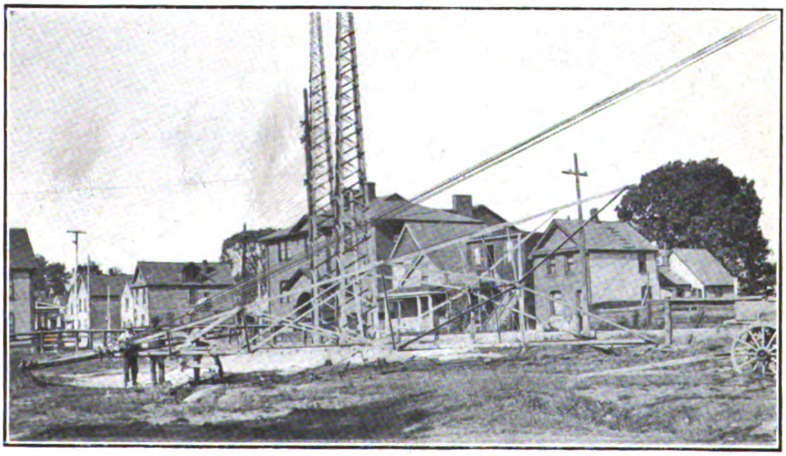
Notes on Guy Anchors

Patent anchors for guying should not be used other than for light construction. In light soil, an old fashioned slug, or deadman, gives the best results. All guys should be periodically inspected and tightened up. When more than one guy is used on a pole, galvanized turnbuckles should be used to obtain best results.



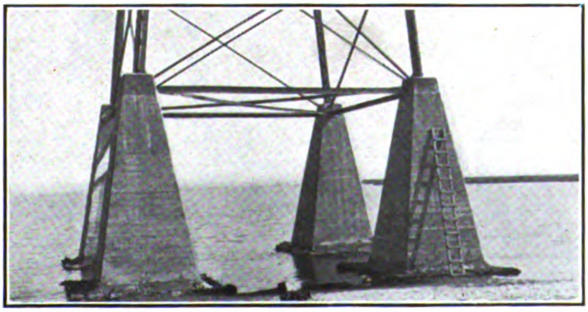
[CONNERY]

FIG. 8—METHOD OF LOWERING STANDARD 40-FT. TOWER—THIRD POSITION



[CONNERY]

FIG. 9—METHOD OF LOWERING STANDARD 40-FT. TOWER—FOURTH POSITION



[CONNERY]

FIG. 14—LAKE TOWER FOUNDATIONS, BURLINGTON BEACH

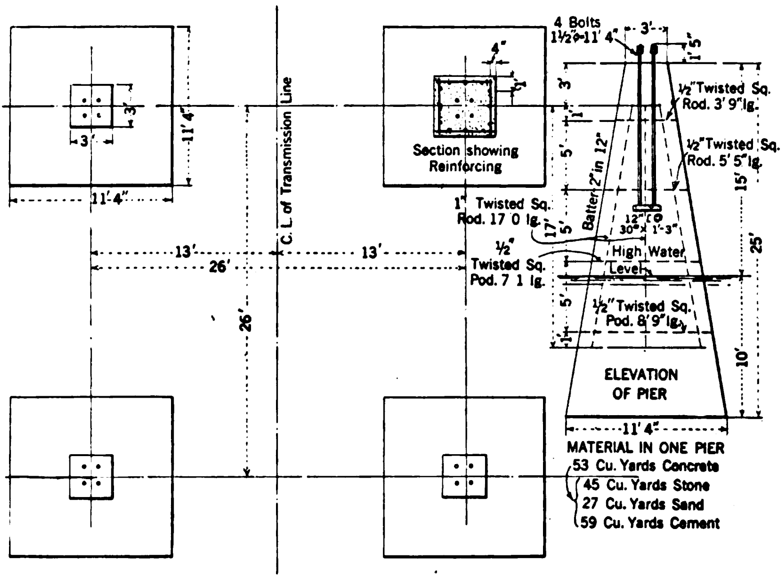


FIG. 11—FOUNDATION PLAN FOR LAKE TOWER

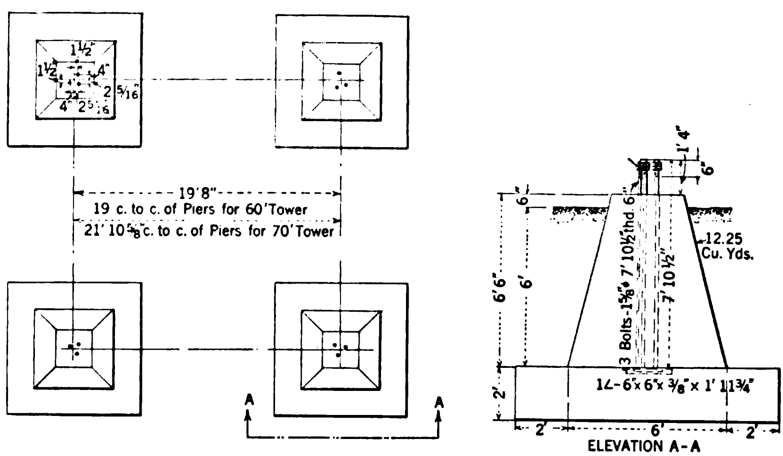


FIG. 12—MASONRY PLAN AND ANCHOR BOLTS

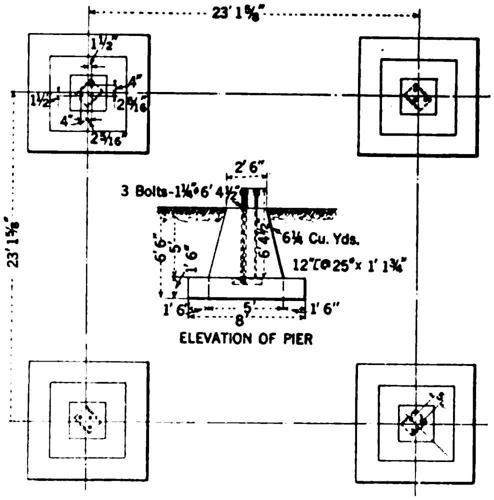


FIG. 13—FOUNDATION PLAN FOR 75-FOOT HEAVY STRAIN TOWERS

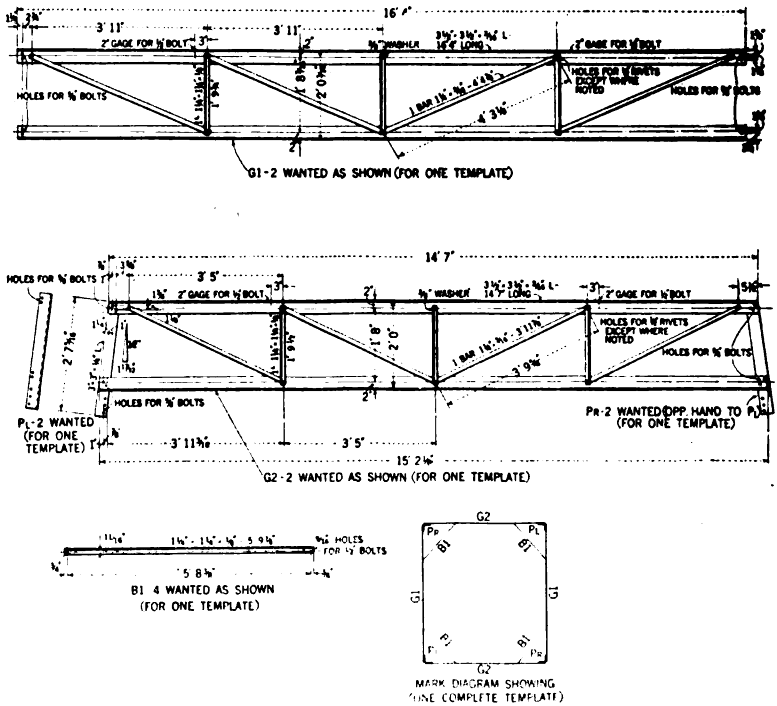


FIG. 15—DETAIL OF TEMPLATE FOR STANDARD TOWER FOOTINGS

From observations extending over ten years, I would say that fully 40 per cent of the guys in use are inefficient, this condition being due to lack of inspection. To obtain the best results in guying, the anchor should be placed at a distance from the base of the pole equal to one third the height.

In using rock-bolts for anchoring, care should be taken, if the rock is covered with a layer of earth, to place the anchor so that the ring is just above the surface of the rock; then fasten a long link to the ring, and guy to this. This method will give much better results than if the ring had been left above the surface of the ground and guy attached to it, as the anchor rod will bend in the latter case. These rock-bolts should be grouted in with hot brimstone.

We are now designing tower footings which include the following points which we submit for consideration and discussion:

(1) A modification of an ordinary screw-type guy anchor, similar to the Matthews or Stombaugh anchor, with the top of the anchor rod shaped to take the tower leg; this for towers of light wind-mill type.

(2) For heavy anchor, long-span, towers, etc. A large foot-plate supported on a shallow concrete footing sufficient to give a good bearing, and an anchor similar to those mentioned above, with the exception that the end of the bolt will be threaded to take a nut and locknut.

(3) For extra heavy, or four-circuit towers. A large section screw-pile with top plate to which the tower foot plate can be bolted.

We also offer for consideration, the question of threading an ordinary wooden pile. There are locations on almost every line where marshy land or muskeg is encountered, and it is usually a very expensive operation to use a pile driving outfit in these locations.

In connection with this method, we have found that it is not necessary to drive a pile to refusal to obtain a good footing for a standard tower, as there is sufficient skin friction developed by the pile in the upper layers of the ground to give satisfactory results. Twenty-five-foot piles have been found satisfactory in very swampy ground, where borings had been taken to a depth of forty feet without striking firm soil.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, at a joint session with the Illuminating Engineering Society, Deer Park, Md., June 30, 1915.

(Subject to final revision for the Transactions.)

THE EFFECTIVE ILLUMINATION OF STREETS

BY PRESTON S. MILLAR

ABSTRACT OF PAPER

This paper mentions the dependence of effectiveness in street lighting upon municipal appropriations and efficient lamps, but discusses more particularly those aspects of effectiveness which are dependent upon skilful utilization of the light to produce the most effective illumination. There are included a classification of streets, a statement of the objects of street lighting and the elements of vision under street lighting conditions. The paper emphasizes three considerations which are sometimes neglected in street lighting discussions; namely, the silhouette effect, specular reflection from street pavements, and glare. The remainder of the paper is given over to a presentation of the variables upon which the effectiveness of street illumination depends, and upon the influence which each feature of the installation exercises through these several variables. As a part of this discussion illuminating efficiency values for the several modern street illuminants are given. The appendix includes statistics and photographs of some very recent installations which illustrate the latest trend in street lighting.

IMPROVEMENT in street lighting involves (1) larger municipal appropriations; (2) more efficient lamps and accessories; (3) greater skill in application.

Larger Municipal Appropriations. The public is gradually becoming acquainted with the advantages of more liberal use of light. Use of the streets at night is becoming more general throughout a greater number of hours. Requirements for good street lighting are becoming greater as traffic becomes denser and as traffic speed increases. Also the advertising value of extensively employed light is commanding appreciation in mercantile lines. These things combined are leading to larger municipal appropriations. Larger appropriations mean betterment in street illumination because the mere addition of lamps with no increase in lighting efficiency and no greater skill in application usually improves conditions. The greatest single obstacle to satisfactory street illumination is lack of funds.

More Efficient Lamps and Accessories. The last two years have witnessed increases of 25 to 50 per cent in efficiencies of street illuminants, the Mazda C incandescent lamp and the

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magnetite arc lamp having progressed contemporaneously. At the present time in the magnetite lamp of medium and high power, in the Mazda C lamp of low, medium and high power, and in the flame arc lamp of high power there are available illuminants having efficiencies four or five times greater than those of various types of enclosed carbon arc lamps which were the principal street illuminants in this country a few years ago. Some advance has been made also in the design of lamp equipments, notable among which are the prismatic refractor and a variety of light-density translucent glassware which combines fairly good diffusion with high transmission. These improvements in the materials of street illumination combined with the increased sums which municipalities are appropriating make possible a very general improvement in street lighting.

Skill in Application. Recently installed systems are almost invariably superior to the systems which they replace. Usually the improvement is due in part to greater skill on the part of the engineers in charge. City engineers, central station engineers and manufacturers are better acquainted with the problems and have acquired more skill in meeting them. The result is street illumination of greater effectiveness. Notwithstanding this advance there are but few principles of street illumination which are regarded as thoroughly established. Although the subject has received perhaps more than a fair share of discussion and study, it is still enveloped in much uncertainty. In the literature and in practise there is much which indicates differences of opinion in regard to principles of fundamental importance. It must be admitted that progress in the conception of correct principles is slow. Yet there is progress, and it may be that by the time most street lighting is made good, those of us who talk and write of the principles may reach an agreement as to what constitutes good street lighting.

It is the purpose of this paper to discuss the variables of street illumination and the principles underlying the best use of modern illuminants and accessories under modern conditions in this country. We shall consider therefore matters pertaining more especially to the third factor entering into improvement in street illumination as enumerated in the first paragraph.*

*This paper may be regarded as a continuation of the discussion presented by the author before the 1910 convention of the Illuminating Engineering Society under the title "Some Neglected Considerations Pertaining to Street Illumination."

Classification of Streets

For the purposes of this discussion the following classification of streets is adopted:

CLASS	DESCRIPTION
1*a*	Metropolitan thoroughfares of greatest distinction.
1*b*	Important city streets largely traveled at night.
2*a*	Business streets not largely traversed at night.
2*b*	City residential streets.
3*a*	Suburban residential streets.
3*b*	Suburban thoroughfares.

It will be apparent that requirements for street illumination are diverse as among these different classes of streets. For example, the 1*a* class of streets is distinguished by a requirement for dignified, pleasing fixtures and for lamps and illumination which should be of fairly high intensity, lighting building fronts as well as street. Streets of the 1*b* class are likely to be characterized by much show-window and sign lighting which augments the street illumination during the hours of greatest traffic. Here intensities are likely to be highest, and the ordinary fundamental requirements of street lighting are supplemented by the desirability for recognizing acquaintances in the passing throng and for detailed vision, approaching that common to interiors at night.

In streets of the 2*a* class a moderate intensity of illumination which lights building fronts as well as street is customary. Policing purposes and good seeing conditions for the occasional pedestrian are the principal desiderata. In streets of the 2*b* class it is usually desirable to keep the light upon the street surface, avoiding brilliant illumination of the upper stories of residence fronts and providing fairly good lighting for the low density vehicular and pedestrian traffic.

In streets of the 3*a* class it is likewise desirable to keep the light upon the street, illuminating the sidewalks well to serve the purposes of pedestrians. In streets of the 3*b* class, which are the important automobile highways connecting populous centers, the principal requirement is that of the automobile driver. Here the most difficult problems of street illumination are encountered.

The discussion in this paper is applicable in varying degree to streets of these six classes.

Objects of Street Illumination

From several points of view the objects of street illumination may be stated in somewhat different ways. The point of view of the motorist differs from that of the pedestrian which in turn differs from that of the police commissioner and from that of the merchant. When, however, one assembles the considerations growing out of all these several viewpoints, those of first importance appear to fall within the comprehensive classification presented by the National Electric Light Association Street Lighting Committee in 1914 which is as follows:

Fundamental Purposes to be Served by Street Illumination.

1. Discernment of large objects in the street and on the sidewalks.
2. Discernment of surface irregularities in the street and on the sidewalks.
3. Good general appearance of the lighted street.

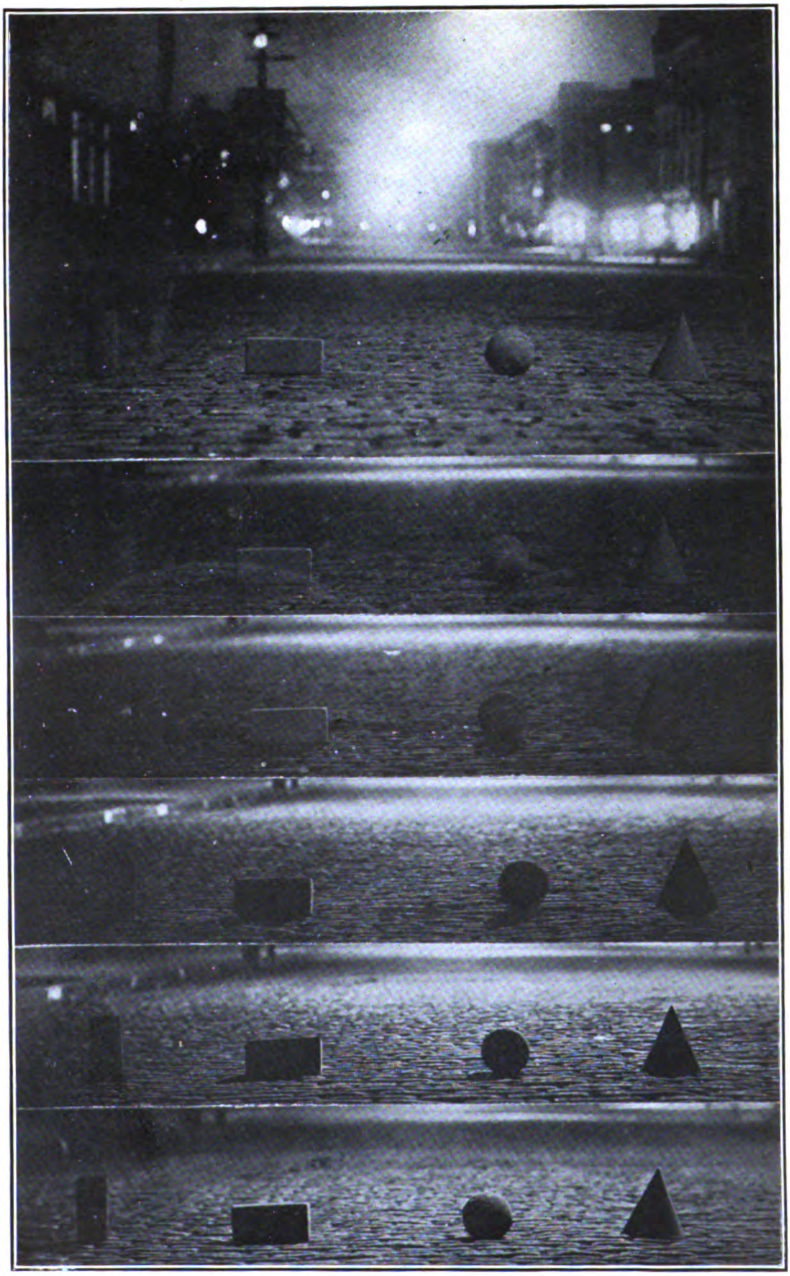
It would appear that in proportion as these three purposes are served the street illumination will be regarded as satisfactory, and it may be concluded that no street lighting installation which serves these three purposes reasonably well can be regarded as unsatisfactory. The weight to be given each will vary in different streets though in a general way it is probable that the purposes are served in the order named. It is possible to install at a low cost a system which will reveal large objects (purpose No. 1) while failing to serve the two other purposes. With increased appropriations, or more efficient illuminants, large objects may be revealed to better advantage and surface irregularities (purpose No. 2) may also be revealed although the third object may not be served. With still larger appropriations and still more efficient illuminants, discernment may be improved and a pleasing appearance for the street (purpose No. 3) by day as well as by night may be had. All three objects may be served when appropriations are adequate.

Processes of Seeing

In streets at night objects are seen by reason of contour, relief, shadow or color.

We perceive the contour of objects when they are markedly different in brightness from their background. Since most large objects on the street at night are darker than their background we perceive them usually as silhouettes.

Contrasts in relief are perceived when the exposed surface of an adequately illuminated object presents areas of different



[MILLAR]

FIG. 1A—TEST TARGETS IN SIX REPRESENTATIVE LOCATIONS AS ILLUMINATED BY TWO DIFFERENT SYSTEMS OF LIGHTING. ILLUSTRATING RELIANCE UPON CONTRASTS AND DIFFERENT KINDS OF CONTRASTS PRESENTED TO VIEW

reflecting powers, or elements which are more or less favorably inclined with respect to incident light, or elements which lie in the shadow of other elements of the surface.

We may perceive small objects by reason of their shadows occasioned by the interception of sharply inclined rays of light. Shadows of large objects are not always of value in promoting discernment and are often misleading as in case of the shadow of a telegraph pole thrown across the sidewalk.

Color contrasts are not usually relied upon since in installations where discernment is at all difficult, color is usually lost and objects are perceived more readily by other means.

The several kinds of contrast perception are suggested in Figs. 1A and 1B, made from a series of photographs of test targets. These have been located successively in six representative positions between lamps in the street shown in Figs. 8 and 9. Fig. 1A shows the lighting effects by the centrally mounted lamps shown in Fig. 8. Fig. 1B corresponds with Fig. 9. The targets are substantially the same color as the street surface. It is to be noted that those which are most clearly revealed receive the least light and are silhouetted against their background. Those least distinctly revealed receive on the observed surfaces about the same light as their background.

Contrast perception is the ruling visual process with which street illuminations is concerned. To increase contrasts on surfaces to be seen is to better conditions for vision.

Some Considerations which are Often Ignored

In much of the literature of street illumination, curves of illumination intensity form the principal basis of judgment as to effectiveness. There is a tendency to over-emphasize the importance of incident light to the prejudice of other important considerations. Three of the principal considerations which are not emphasized directly by study of illumination intensity curves are presented in the following paragraphs.

*Silhouette Effect.** When the writer directed attention to the silhouette effect in 1910, there existed but little appreciation of its importance. During the five years which have intervened there has gradually developed a greater appreciation of the extent to which it enters into conditions of visibility in street illumination. Yet its very general applicability even

*An Unrecognized Aspect of Street Illumination. Millar, Transactions I. E. S., 1910, page 546.

now is unrecognized by some engineers. There is an impression that only in lighting of very low intensity is it the prevailing method of discernment. As a matter of fact the silhouette effect is pronounced whenever there are bright street or building backgrounds. A photographic under-exposure of any street in the daytime shows objects as silhouettes. The casual glance of an automobile driver corresponds roughly with such an under-exposure. The majority of observations of large objects on the streets in our more intensely lighted thoroughfares, especially in the practise of automobile drivers, falls under this heading, because a driver is concerned primarily with avoiding obstacles and usually looks carefully enough only to detect the presence of pedestrians and other objects. Usually he sees these as dark objects silhouetted against the lighter

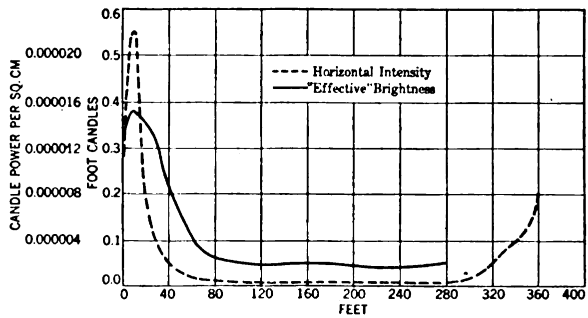


FIG. 3—CURVES OF BRIGHTNESS AND ILLUMINATION INTENSITY

street surface or building surfaces. The pedestrian too obtains distant views of large objects as silhouettes, but as he moves more slowly and approaches objects more closely, he has opportunity for closer observation, and in the more brightly lighted streets supplements discernment by silhouette with actual observation of surfaces in relief.

Figs. 5A and 5B show illustrations made from the original silhouette photograph illustrating the importance of this effect in street lighting.

Nature of Street Pavement. Modern streets which require greatest care in lighting are traversed by automobiles. The majority of them are paved with asphalt, asphalt block, wooden block, treated macadam, etc. As a result of automobile traffic such pavements become oiled and polished. The high spots

[MILLAR]

FIG. 2—VIEW IN COLUMBUS CIRCLE, NEW YORK CITY. NOTE SPECULAR REFLECTION FROM THAT PART OF PAVEMENT WHICH IS TRAVERSED BY AUTOMOBILES. NOTE ABSENCE OF SPECULAR REFLECTION FROM IMMEDIATE FOREGROUND, WHERE THERE IS NO AUTOMOBILE TRAFFIC

[MILLAR]

FIG. 5A—ORIGINAL STREET LIGHTING SILHOUETTE PICTURE. ILLUSTRATING IMPORTANCE OF BRIGHT STREET SURFACE AND SHOWING HOW THE AUTOMOBILE IS DISCERNED BECAUSE THE STREET SURFACE BEYOND IT IS BRIGHT, NOT BECAUSE THE LIGHT FALLING UPON IT RENDERS IT VISIBLE. FOR A DEMONSTRATION OF GLARE SEE FIG. 5B.

First, actual diminutions in ability to perceive small contrasts in the presence of a bright light source.

Second, distraction of attention as a result of which small contrasts may not be perceived when viewed casually.

Third, a temporary dazzling effect which persists for a few moments after a bright light source is viewed directly.

Figs. 5A and 5B illustrate the effect of glare. In Fig. 5A the nearby light source is removed. In Fig. 5B the presence of the light source distracts attention from the automobile and the view is rendered less pleasant. In fact there is a little discomfort involved in looking at the automobile. Nevertheless if one deliberately dispells the idea of the glaring source from his mind and concentrates on the automobile, it can be seen just as well in either illustration. These pictures further illustrate the importance of securing adequate separation between the light source and the observed object, the distraction due to the light source being greater relatively when the picture is held at a distance from the eye and the visual angle between the source and object is decreased.

If a single brilliant light source, as a bare Mazda C lamp is located over a dirt road in the country, the glare is very bad. If the lamp is raised to a greater height or moved to one side of the road, or if the lamp is enclosed in a diffusing globe, the glare is lessened. If a number of additional lamps are strung beyond it along the road, the glare is further reduced. If the lamps, instead of being located over a dirt road, are located over a treated macadam road, or better still, over an asphalt road, the glare is less serious. Light colored buildings along the street also assist reducing the glare. In short, anything which reduces the contrast between the light source and the road surface, or which increases the illuminated area within view, or which separates the bright light source from the road surface, reduces the effect of glare.

Sweet in 1910* studied that part of the effect of glare which is a measureable reduction in the ability to see, using a single light source in a dark room. He found under these exaggerated conditions that a large reduction in visual power could be traced to the presence of a bright light source close to the center of the field of vision. In 1914† working with others on the

*"An Analysis of Illumination Requirements in Street Lighting" *Journal of Franklin Institute*, 1910.

†*Electrical Review and Western Electrician*, March 6th, 1915.

campus of the University of Wisconsin, he pursued his researches, and has given preliminary publication to some very interesting results. In this latter research he employed from two to four lamps mounted at various heights and with various spacing intervals over a dirt road about 350 feet long. It is not proposed at this time to enter into a discussion of these tests, but it may be noted that the only conclusions which they can indicate are those which would apply to a short stretch of dirt road. The modifications introduced by street pavements of better reflecting qualities, by building along the street, and by a greater length of illuminated street, have no part in this research. This is a serious limitation, because the effect of glare in street lighting is very largely reduced by each of these three factors. The two researches make available valuable information which has its bearing upon street lighting principles. If, however, the data are considered without due regard to the limitations under which the tests were made, there is danger of forming an exaggerated idea of the importance of adopting measures which will reduce the effect of glare by decreasing the brightness of light sources to low values. Since the problem is really one of reducing contrast between the light source and the illuminated surfaces, the more constructive way of accomplishing the desired end is to increase the brightness of the illuminated surfaces rather than to dim the light sources unduly. Excessive brightness of light sources must of course be reduced. It is common experience that a simple diffusing globe accomplishes this reasonably well under most conditions. Too great reduction in the brightness of the light source is unsatisfactory psychologically. We like a bright light source—we are dissatisfied with illumination in which a bright light source is not visible. Therefore the thing to do is to eliminate glare by increasing the brightness of the street surface, and where desirable, that of surroundings, and by reducing the brightness of the light sources moderately throughout the angles at which they are viewed.

With these considerations concerning the importance of the silhouette effect, specular reflection from pavements and glare well in mind, we may proceed to a discussion of the variables of street illumination and of the several factors which the engineer must study in planning a street lighting installation.

Illumination Variables

The effectiveness of street illumination depends upon the following:

Intensity of Light upon the Street. There is no single measure of intensity which serves all purposes. The average horizontal intensity upon the street surface is most nearly satisfactory.

Brightness of Street Surface. Adopting automobilist's viewpoint as to angle and direction.

Relation between Lamps and Street Surface. Visual angle between the two, and extremes of contrast encountered.

Contrasts Produced on the Street Surface and on Objects on the Street. This is largely a function of the direction of the light.

Portion of Total Field of View Illuminated. This may be affected either by the number of lighted lamps within view or by the area of surface which is illuminated.

Appearance of Installation and of Street by Day and by Night. Lamps, fixtures, light distribution, etc.

Installation Factors

Each of the foregoing variables upon which street lighting effectiveness depends is affected by four or more principal installation factors. These are listed in the first column of Table 1, in which the variables are given as column headings. The purpose in presenting this table is to emphasize the complexity of the street illumination problem and to indicate the manner in which the several elements are interconnected. Consider, for example, street surface brightness as a variable in street illumination. The table indicates that brightness depends upon the power of the lighting units, the number of lighting units per mile, the kind of lighting accessories employed, the location of lighting units, the nature of the street pavement and the nature of the surroundings. Alteration in any one of these conditions may influence the brightness of the street and therefore the effectiveness of the street illumination. An engineer who considers any one installation condition must appreciate that his decision may be far-reaching in its influence upon the effectiveness of the lighting, since every installation factor influences a number of these variables. Every street presents its own problems, and the utmost effectiveness of street illumination for a given expenditure is had when each factor is applied with due regard to the relations set forth in this table.

In attempting to discuss these several elements of the problem it is necessary to generalize, and this in spite of the fact that the great differences in streets of the several classes listed

TABLE I. EFFECTIVENESS OF STREET ILLUMINATION.

Installation factors which determine effectiveness	Variables (Influences through which Factors Operate)					
	Intensity of light on street	Brightness of street	Relation between lamps and street surface†	Contrasts on street	Portion of field of view illuminated	Appearance of installation and street, day and night
Power of lighting units	*	*	*	*‡		*
Number of ltg. units per mile	*	*	*	*	*	*
Kind of accessories	*	*	*	*	*	*
Kind of mount						*
Location of lighting units	*	*	*	*	*	*
Nature of pavement		*	*	*		*
Nature of surroundings	*	*	*	*	*	*

†Visual angle and extent of contrast.
‡Visibility not ratio of reflection coefficients.

on page 1381 makes generalization difficult. Nevertheless it is hoped that a general discussion of the influence of each factor upon the several variables will be of value, particularly since it is proposed to note principally those features in which recent experience has suggested some new consideration.

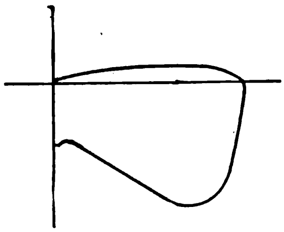
Size of Lighting Units and Spacing Intervals

Power of Lighting Unit. There is now a general tendency toward the adoption of more powerful lamps of one of the three types listed in Table II. These data are available through the courtesy of the Lamp Committee of the Association of Edison Illuminating Companies; in large measure they are authoritative for lamps of the period stated and equipped as indicated. Of the above illuminants the flame arc lamp and the multiple Mazda C lamp depreciate in candlepower 20 to 25 per cent throughout life. The magnetite lamp and the series Mazda C lamps do not change materially throughout life.

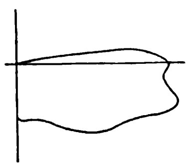
Large Versus Small Illuminants. The cluster of lamps employed so largely in "ornamental or white way" lighting during the past five years has yielded favor in most recent installations to the single illuminant or less frequently to twin illuminants on one post.

The effectiveness of the light, other things being equal, is dependent upon the choice as between many small lighting units and few large lighting units. In favor of the small illuminants it is urged that greater uniformity results from their use; that they may be mounted lower, thus avoiding shadows from trees, etc; and it is added that when small illuminants are mounted low, a larger percentage of their total flux is distributed over the street surface. On the other hand, it is argued in favor of large illuminants that they are relatively less costly per mile, and that usually the appearance of a street lighted by them is more pleasing.

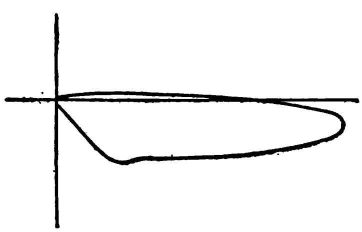
There are two considerations not usually urged in this connection. The first is discussed in more detail under the subject of location of lighting units. Large illuminants are favored from this viewpoint because they may be placed well out over the middle of the street, where the specular reflection from street surfaces allows the light to be applied in a more favorable direction than that from small illuminants which usually are mounted low over the curb. Fig. 11 is an excellent illustration of the advantageous use of large units in lighting a country



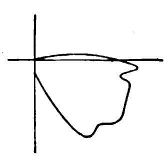
A—Flame Arc Lamp. Clear Globes



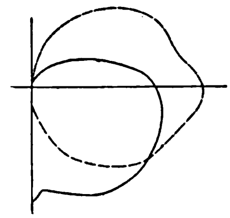
B—Magnetite Reflector and Clear Globe



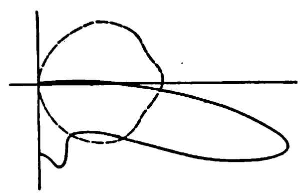
C—Magnitite, Refractor and Clear Globe



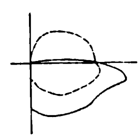
D—Metallic Flame Reflector and Clear Globe



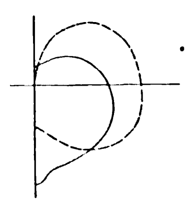
E—Mazda with Diffusing Globe



F—Mazda with Reflector and Refractor



G—Mazda, Radial Wave Reflector



H—Mazda with Diffusing Globe

Distribution characteristics referred to in Table 2. Broken line indicates bare lamp.

A—Fl

B-

C—M

D—

Distrib

road. The lamps are placed 500 to 900 feet apart and 18 to 25 feet high. The effect is good for automobile driving purposes. An example of ineffective use of small illuminants will occur to all who can visualize a wide, wet street with lamps over both curbs. The lighting of the street surface consists of a few bright streaks near the curbs, while the middle of the street is dark. Fig. 6 illustrates this effect upon a dry pavement. As modern street pavements are extended, and automobile traffic increases, the advantages of mounting lamps well over the center of the street tend to increase, and the disadvantages of small illuminants mounted low over the curbs tend to become more apparent.

The second consideration was brought out prominently last year by the Street Lighting Committees of the National Electric Light Association and the Association of Edison Illuminating Companies. It was shown that within reasonable limits, uni-directional light is to be preferred to multi-directional light because it enhances contrasts upon which discernment is dependent. Objects and surface irregularities are seen more surely by uni-directional light than by light coming from a number of directions. From this it follows that, other things being equal, the revealing power of a few large illuminants is greater than that of many small illuminants, especially if the latter are staggered along both curbs.

While these considerations do not clearly indicate the desirability of large units, they do add weight to the arguments in their favor.

Lighting Accessories

Improved Distribution. The most desirable distribution of light depends largely on the nature of the street surface and on the character of the street. Hence there is no such thing as a correct distribution characteristic for all street lighting. The prismatic refractor is successful in providing a distribution characteristic which for a vertical plane conforms to the theoretical requirements as laid down by some engineers. In other forms it will doubtless provide different distributions as required. It is an admirable device so far as re-direction of light is concerned. However, it is objectionable in some forms because of excessive brightness, due to its small size. Also when combined with the casings with which it is usually employed, its appearance is not attractive. Probably in the evolution of this useful device these objections will be overcome.

The same considerations which underlie the design of the refractor, namely the desire to increase the intensities on street surface at a distance from the lamps, would appear to favor the adoption of assymetrical horizontal distributions whereby light which normally is delivered upon surfaces lying along the sides of the street, is directed upon the street surface. Lighting accessories to accomplish this purpose have been devised but thus far have not received the extensive trial which their theoretical advantages would appear to warrant.

Diffusing Globes. The employment of diffusing globes to decrease brightness of light sources in the street has become more general in recent years. Perhaps the extreme example in the way of increased size of such globes is found in the Washington, D. C. installation of ornamental magnetite lamps, in which 28-inch built up alabaster globes of rather high density are employed. (See Fig. 7). As compared with the use of a clear globe or of a lamp with no globe, a diffusing globe of fairly large size is usually desirable because it improves the appearance of the lighting unit, renders the appearance of the street more pleasing and promotes good conditions of visibility.

It is desirable to secure the best possible balance between low light absorption and good diffusion when selecting diffusing globes. Test data on these two characteristics are of importance and should not be neglected. Because of neglect of simple and inexpensive tests of commercially available glassware, globes are being installed which do not accomplish the purposes in view so well as would other glassware. These either absorb a larger percentage of light than is necessary to secure the desired degree of diffusion, or else diffuse less well than need be, considering the amount of absorption.

Protection for the Eyes. At first glance it would appear that street lighting purposes would be served admirably by a lighting accessory which would concentrate a large proportion of the light flux upon the street surface while directing but little light at those angles which fall near the center of a field of vision in a given installation. However, certain difficulties operate against the success of such a scheme. With practicable mounting heights, spacings have to be short if this is to be successful in illuminating the entire length of the street. The general direction of the light in such an installation is much more largely downward than is usually the case. Wherever there are sufficiently short-interval spacings to allow of such

[MILLAR]

FIG. 7—MAGNETITE LAMPS IN 28 INCH GLOBES AS USED IN WASHINGTON, D.C.

an installation, there usually exists a requirement for lighting the building fronts. In such installations the relatively high intensities on the street surface, together with the large areas of considerable brightness which present themselves to view, render the glare negligible when ordinary diffusing globes are used. That is to say, in the only installations where it is practicable to use such devices, their eccentric distribution characteristics are unnecessary. Where the surroundings are such that the lighting of building fronts is undesirable or unnecessary, spacings are usually too great to admit of the use of such devices, because their illuminating range is too small. Also considerations of street surface characteristics, discussed elsewhere, suggest that suppression of light at say 80 deg. may do more harm by lessening the pavement brightness than can be compensated by decreased brightness of source.

Location of Lighting Units

Comprehended under this heading fall such subjects as height, transverse location and spacing. In most city installations these aspects are standardized for a particular street. In lighting of interurban roadways, lamps are sometimes located in accordance with best judgment, varying considerably in all these particulars.

Location Transverse of Street. As between center and curb locations there is a considerable difference. In the first place with lamps located over each curb, the street appears much wider, as is illustrated by a comparison of Figs. 8 and 9 which are alternate test installations of the N. E. L. A. and A. E. I. C. Street Lighting Committees.

In the lighting of important city streets this is usually a desirable condition. The lamps mounted over the curbs likewise illuminate the sidewalks and the fronts of buildings better (See Figs. 16 and 19). When, however, the lighting of the roadway becomes of first importance, as in streets of the 3*b* class, the best use may be made of the light by locating the lamps as nearly as practicable over the roadway so as to take full advantage of all specular reflection from the street surface. (See Figs. 11 and 6).

Height. In regard to heights of lamps there is also a wide difference in requirements, depending upon the character of the street. In some of the latest practise, powerful lamps are located 14 to 18 feet over the curbs on business streets. These,

however, are backed by light colored buildings and the entire surrounding is so brightly lighted that the glare is not bad. With lamps over the middle of the street the background is usually the dark sky, and usually there are not light colored buildings to relieve the general darkness. Under these conditions the opportunity for glare to become serious is considerable and it is therefore necessary to locate the lamps rather high. The improvement realized in increasing the height of lamps of moderate power from 18 to 20 feet is considerable, while the improvement in increasing the height from say 27 to 30 feet is not very great. The curve of glare falls off rapidly with increasing separation when the separation between the light source and the observed surface is only a few degrees. Around a lamp which has a dark background there is a zone of halation within which objects tend to become invisible. Once outside this zone, the glare effect falls off less rapidly. It is very important to mount the lamps high enough to insure that the separation from the street surface is at least sufficient to avoid this zone of serious glare.

Power of Unit as Related to Glare. Other things being equal, the objectionable effects of glare are greater when the lighting units are more powerful. Hence it is approved practise to mount the more powerful units higher than less powerful units.

Such a lack of separation is responsible for the serious glare illustrated in Fig. 10. An arc lamp is located over the inside of a curve in a road obscuring the roadway beyond. The angle of separation between lamp and roadway is about 3 degrees. Fig. 11 shows the same road but with a lamp located over the outside of the curve and separated from the distant roadway by about 20 degrees when viewed as in driving. It must be recognized that a bright light source obscures its immediate background. This obscuration is greater if the light source is brighter or more powerful, and is less if the background is brighter. In country roads or park drive lighting such obscuration is often very serious. The illustrations in Figs. 10 and 11 indicate one good way of overcoming this difficulty. Recognizing the truth that under such conditions the bright light sources will obscure a certain region of the field of view, the source is so located that the background which it obscures is one which it is not important to see and that the surface which it is desired to see is sufficiently separated from the glaring light source to avoid difficulty.

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FIGS. 8 AND 9—CENTER VERSUS CURB MOUNTING IN THE SAME STREET

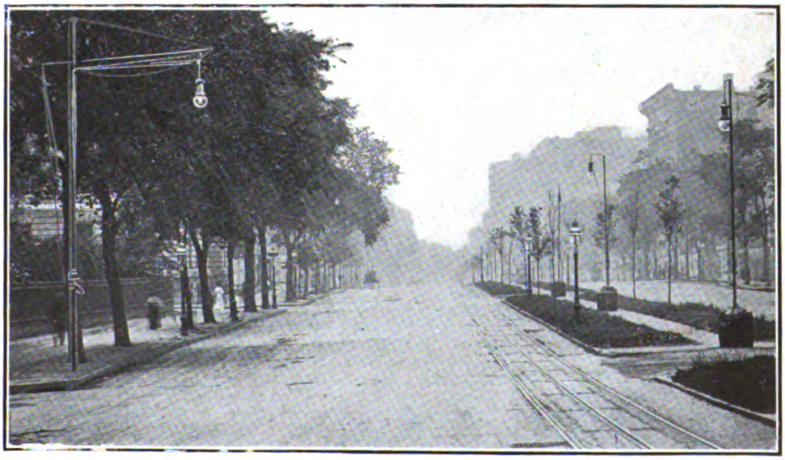

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FIG. 12—ADJUSTABLE TEMPORARY INSTALLATION EMPLOYED IN NEW YORK CITY TO DETERMINE BEST LOCATION FOR LAMPS

[MILLAR]

FIG. 10—VIEW OF COUNTRY AUTOMOBILE ROAD. LAMP WRONGLY LOCATED ON INSIDE OF CURVE. GLARE OBSCURES VIEW OF ROAD BEYOND

[MILLAR]

FIG. 11—VIEW OF SAME ROAD SHOWN IN FIGURE 10. LAMP ON SIDE OF CURVE REPLACED BY LAMP IN THE LEFT OF VIEW. CHANGE OF LOCATION ENABLES ROADWAY TO BE SEEN. NOTE SPECULAR REFLECTION FROM ROADWAY DUE TO LAMPS 600 AND 1000 FEET AWAY. EXCELLENT CONDITIONS FOR DRIVING WITH LARGE ILLUMINANTS (MAGNETITE ARC LAMPS WITH REFRACTORS) WIDELY SPACED

[MILLAR]

FIG. 13—CARLISLE, PA. 600-CP. MAZDA C LAMPS IN PRISMATIC REFRACTOR UNITS, SPACING 250 TO 500 FT., HEIGHT 18 TO 22 FT.
Photograph by courtesy Edison Lamp Works.

[MILLAR]

FIG. 14—FOURTEENTH STREET, WASHINGTON, D.C. 100-CP. MAZDA C LAMPS ABOUT 10 FT. ABOVE CURBS, SPACED AT INTERVALS OF 80 FT. ALONG EACH CURB
Photograph by courtesy W. C. Allen, Electrical Engineer, District of Columbia.

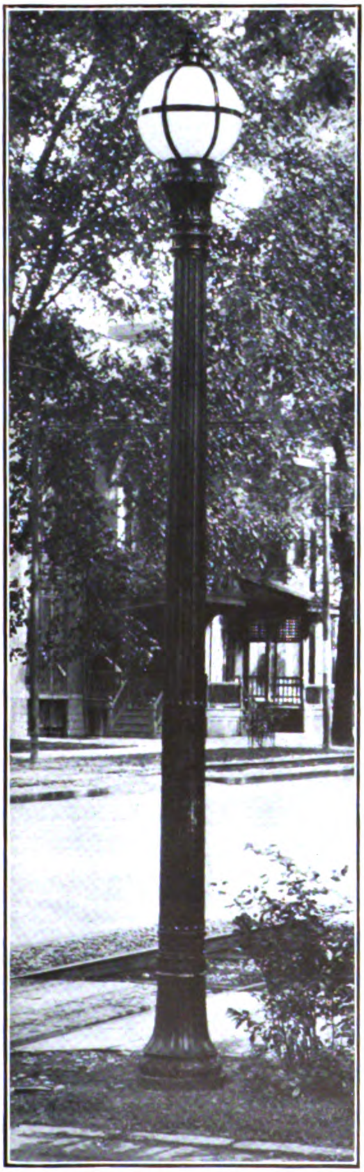

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FIG. 15—LAKE AVENUE, ROCHESTER. 500-WATT MAZDA C LAMPS, MOUNTED 17½ FT. ABOVE CURB, SPACED AT AVERAGE INTERVALS OF 225 FT.

Photograph by courtesy Rochester Railway and Light Company.

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FIG. 18—MAIN STREET, ROCHESTER. 6.6-AMPERE MAGNETITE LAMPS, LOCATED 14½ FT. ABOVE CURB AND SPACED AT 100-FT. INTERVALS ALONG EACH CURB

Photograph by courtesy Rochester Railway and Light Company.

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FIG. 16—FIFTH AVENUE, NEW YORK. 400-WATT MADZA C LAMPS ON TWIN POSTS, MOUNTED 19 FT. ABOVE CURB AND SPACED AT ABOUT 100 FT. INTERVALS ALONG BOTH CURBS WITH EXTRA LAMPS AT CROSS STREET INTERSECTIONS

Photograph by courtesy The New York Edison Company

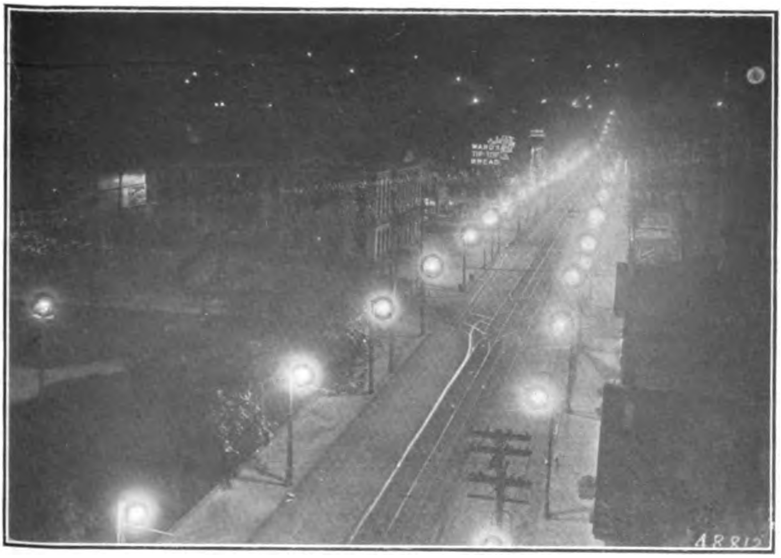

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FIG. 17—FEDERAL STREET, PITTSBURGH. SERIES A-C. FLAME ARC LAMPS. WHITE LIGHT CARBONS. LAMPS MOUNTED 24 FT. ABOVE CURB AND SPACED AT AVERAGE INTERVALS OF 69 FT.

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FIG. 19—PENNSYLVANIA AVENUE, WASHINGTON, D.C. 6.6-AMPERE MAGNETITE LAMPS AS ILLUSTRATED IN FIG. 7. MOUNTED 15 FT. ABOVE CURB, SPACED AT 50 FT. INTERVALS ALONG BOTH CURBS

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FIG. 20—FIFTH AVENUE, PITTSBURGH. 6.6-AMPERE MAGNETITE LAMPS, MOUNTED 18 FT. ABOVE THE CURB, SPACED AT APPROXIMATELY 80 FT. INTERVALS ALONG EACH CURB

Spacing. All features of an installation should be treated in such a way as to avoid dark areas between lamps, coupled with low mountings for very bright and powerful lamps. To avoid ineffective results due to multi-directional light which reduces contrasts, spacings need to be greater when the lamps are staggered along both curbs than when they form a line along one side or over the middle of the street. The best spacing would appear to be contingent upon the kind of pavement employed and the nature of the surroundings. All the other factors should be so handled that in driving, one will not encounter the bad condition of a bright light source preventing an adequate view of the surface of the street beyond it.

Fig. 12 illustrates the very excellent practise which is sometimes followed in the City of New York, in locating lamps for street lighting. Lamps which are temporarily installed may be raised and lowered; those mounted from the mast arm post may be placed nearer to or farther from the curb, and those in the center parkways may be moved about at will, the posts being mounted in rock-ballasted barrels. A crew of men locate the lamps in the trial installation as directed by the engineers in charge and the locations which appear to give the best illuminating effects are arrived at. Photometric tests are then made to show the results obtained and to afford a basis for the planning of other installations.

Theoretical Considerations which have not been Demonstrated

Color. In street illumination where intensities are low, it is believed by some engineers that white light is more effective than yellow light. According to this view, objects are revealed with greater definition; smaller contrasts may be perceived, and there is less suggestion of haziness in the atmosphere when white light is employed. In accordance with the Purkinje effect there would appear to be some basis for this theory, since it is well known that at intensities of the order of 0.01 foot-candles, we see almost exclusively by rod vision and the maximum of the ocular luminosity curve is removed toward the blue end of the spectrum. Whether or not this effect is present in street lighting is one of the interesting subjects of speculation at the present time.

Whether or not white light possesses advantage for low intensity street lighting due to ocular peculiarities, it is certain

that it is preferred by many for high-class street lighting on the ground that it is more suitable, pleasing and dignified than is yellow light. This is perhaps a matter of color association and is surely a matter of taste. It therefore hardly finds place in a discussion of this kind, and is merely mentioned in passing.

"Animation" of Light Source. It has been suggested that the slight fluctuation of light which characterizes arc lamps possesses some advantage for street lighting purposes over the steady glow of the incandescent lamp. So far as the writer knows, no demonstrations have been undertaken, and it has not been shown that this speculation has any basis in fact.

General Status of the Problem of Street Illumination

There is an important consideration suggested in the first paragraph of this paper. As more money is expended on street lighting and as more efficient lamps are made available, the intensities of light in streets become greater. As the intensities increase, the requirements for the best possible application of light to promote good visibility conditions become less severe and the requirements for application which improve the appearance of the street become more urgent. From the standpoint of rendering visible the street and objects upon it, the lighting of suburban automobile roads where but little money is available for installation and operation offers the best test for the engineer's skill. In first-class streets we have already progressed to the point where aesthetics assume large importance. This does not mean, however, that the problems of street lighting are becoming less difficult; it means simply that the problems are becoming more involved, and broader comprehension of the fundamental principles of street illumination is becoming more essential.

Appendix. In the appendix will be found some statistics of very recent installations in streets of several classes showing practise in this country as of the early part of 1915. These are accompanied by a few illustrations.

Acknowledgment. The author wishes to express his indebtedness to a number of gentlemen who have kindly supplied some of the photographs for illustrations and the statistics which are utilized in this paper, and who are too numerous to permit of individual mention in this connection.

City and Street	Descriptic		Building fronts lighted?
	Width of roadway in feet	Kiccessories	
Pittsburgh, Pa. Fifth Avenue....	36	Busm alabaster	Yes.
Pittsburgh, Pa. Federal Street....	47	lobes	
Chicago, Illinois Dearborn Street..	42	Bulobes	Yes.
Rochester, N. Y. Main Street......	80	Buter globes	
Hartford, Conn. Main Street......	90. ft bet. bldg. lines	Buix, Form 1.	
Washington, D. C. Pennsylvania Av.	109	Ali segmented aster globe e upper, me- lower hemi-	Well
New York, N. Y. Fifth Avenue. (25 to 58 Sts.)	60	BiCarrara globes	Yes.
Corning, N. Y. Market Street		Bi I. globe and cent glass rs	
Rochester, N. Y. Lake Avenue.	50	Rister globes	
Milwaukee, Wis. Grand Avenue.	92	Bi alabaster es	Yes.
New York, N. Y. Seventh Ave (110 to 136 Sts.)	80	Ai ventilated inlight Carrara	
Chicago, Illinois Troy Street.	36	Ri obes	No.
Washington, D. C. Sixteenth Street.	50 ft. (160 ft. bet bldg. lines).	Ri Alba globes	

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To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 30, 1915.

(*Subject to final revision for the Transactions.*)

THE CLASSIFICATION OF ELECTROMAGNETIC MACHINERY

BY F. CREEDY

ABSTRACT OF PAPER

The author proposes to classify all dynamo electric machinery according to five sets of characteristics, as follows:

1. Type of field, as constant intensity, variable intensity, multiple polarity and homopolar.
2. Method of disposal of secondary power, which may be zero wattless, utilized in separate apparatus or transformed and returned to the line.
3. Use of commutators, which may be on either the primary or the secondary, or may be absent.
4. Method of magnetization, namely, high frequency magnetization as in the ordinary induction motor and low frequency magnetization as in synchronous and compensated motors.
5. Method of connection. Many types may be connected either in series or shunt. A tabulation of these characteristics is given, by reference to which any dynamo electric machine can be classified.

THE FOLLOWING paper is an attempt to arrive at a natural classification of the electromagnetic machine. One of the principal uses of such a classification is to bring out the common points of different types which are usually regarded as totally distinct even though they are almost identical from the constructional standpoint, and to reduce their differences to proper relative proportions. The disadvantage of a paper on classification like the present is, of course, that one is reduced to a somewhat bare catalogue of possible types and their characteristics, whereas the real interest of the subject lies in the detailed description of the more important ones. We may preface our discussion by a few general remarks.

1. No discussion will be attempted of homopolar machines which form a class entirely apart from all others.

2. While almost all the machines described may be used as generator or motor, they will in practise be used only as motors, since the requirements of a generator are so uniform that there is no scope for a large variety of types, while the infinite variety of industrial work gives rise to a corresponding variety of types of motor. In generators the tendency is to uniformity

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and in motors to variety, and hence our subject might almost as well be called "The Classification of Electric Motors."

3. For a similar reason, viz., the powerful tendency towards standardization, and the necessity for one system of distribution catering to a vast variety of applications, together with the urgent necessity of economy due to the great length of transmission lines, we may dismiss from our minds the likelihood of new and more complicated systems of transmission arising, although several such are imaginable, and confine our attention to machines operating from standard direct-current, single or polyphase systems.

4. Of the two distinct constructional forms in use, viz., the type having uniformly slotted stator and rotor and a constant air gap all round, and the salient pole type, we shall consider the former as universal and ordinary, and the latter as a special case applicable to certain types only.

5. In all the discussions below, unless a statement to the contrary is made, we shall treat our machines as "ideal", *i. e.* entirely devoid of all losses and leakages.

6. Theories come and go, while the machines we wish to classify remain the same. Our methods of classifications should be of a fundamental nature and should not owe their validity to the acceptance of a particular theory, nor should they be unintelligible to those who have not gone through a particular course of study. They should be based either on constructional features, where these can be proved to have a general significance and not to be accidental, or on mechanical considerations in connection with torque, power and energy. These considerations apply to nomenclature also, and should render us very conservative in inventing new names for old apparatus.

A well understood name, even though based on an obsolete theory is usually better than a new name based on a theory which may become obsolete in its turn.

Having cleared the ground by the above considerations we may proceed to our main subject.

We shall regard the induction machine or "general alternating current transformer," as Steinmetz calls it, as fundamental, and shall proceed to derive all other types from it.

Our general dynamo electric machine, then, consists of two concentric magnetic elements, separated by an air gap, and capable of relative rotation. Each of these elements bears a number of conductors disposed next the airgap in slots parallel to the

shaft. The conductors of one or both elements are interconnected in such a way as to give rise to a definite number of poles, conductors being led off from the stationary element direct to the line, save in a few cases where it is short-circuited. The rotor may be of three distinct types (a) short circuited (b) fitted with collector rings (c) fitted with commutator. Every type of dynamo electric machine whatsoever with the exception mentioned above may be built in a form covered by the above description and the differences between different types consists merely of differences in the method of connection to the line and of connection between rotor and stator.

We have next to classify these types of connection and show why they are required. In order to do this we must first consider our electric system as a machine. From the mechanical point of view then, the generator is a gearing which transmits the motion of the prime mover to the polyphase line, changing the power given out by the prime mover from the mechanical form to that of a rotary system of electrical stresses revolving at a definite speed, say of 25 or 60 cycles, (or revolutions) per second. The polyphase line we may compare to a mechanical line shaft transmitting the power to a distance and the motor to another gearing, retransforming the power into a mechanical torque operating at a certain speed.

What will this speed be? To determine this, consider the following relation which it is well known exists between the speed and primary and secondary frequencies of the induction machine. Speed (rev. per sec.) $\times$ no. of pole pairs = difference between primary and secondary frequencies (cycles per sec.) or mechanical speed of rotor equals speed of wave relative to stator, minus speed of wave relative to rotor,

or

$$S = W\ (f_1 - f_2) \qquad (1)$$

where W is twice the polar pitch.

These equations show that we cannot tell the mechanical speed of the rotor unless we know the rotor as well as the stator frequency. Multiplying both sides of this equation by the torque we get T multiplied by mechanical speed equals T multiplied by speed of wave relative to stator minus T multiplied by speed of wave relative to rotor; or, mechanical output equals primary electrical input minus secondary electrical output. (2)

This equation shows that besides the mechanical power and the electrical input into the primary, there is a certain amount of

power generated in the secondary proportional to the secondary frequency. The above simple considerations bring us to our first principle of classification. It has been emphasized above that the motor is a device for changing electrical power incoming from the line into mechanical power, and hence the existence of this secondary power raises a series problem—what to do with it. We shall classify our machines first according to means adopted for disposing of the secondary power. A substantially identical principle for adjustable-speed motors may be deduced from the equation (**1**) above.

This equation shows that the speed can only vary

1. If the primary frequency varies,
2. If the secondary frequency varies,
3. If the number of poles varies,

and we may classify adjustable speed motors according to which of these means is adopted to vary the speed. Before proceeding further we shall develop a mechanical analogy between our induction machines and certain types of epicyclic or differential gears which is capable of being carried into considerable detail, and throws a great deal of light on the real nature of many arrangements of machines. This analogy enables us to abstract entirely from the electrical features of the problem and consider power and torque alone. We shall show also, that we compare the relative speed of the two elements of our machine to the speed in revolutions per second of one shaft of a differential gear, and the frequencies in the two members to the speed of the other two shafts, the above relation between speed and frequencies corresponds to that between the speeds of the three independent shafts of the differential gear. Such a gear is shown in Fig. 1.

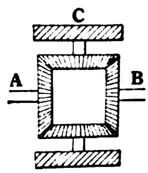

FIG. 1

If the shafts A, B and C' go at speeds of A rev. per sec., B rev. per sec., and C' rev. per sec. respectively, it is well known that C' will be the mean of A and B, or $C' = \frac{1}{2}(A + B)$.

If therefore, we gear another shaft C to the shaft C' so that the speed of C is twice that of C', or $C' = \frac{1}{2}C$, we shall have

$$C = A + B$$
$$B = C - A$$
$$A = C - B$$

Or, in order to introduce a constant, corresponding to the "number of pole pairs" in the electric machine, we may sup-

pose B or A geared to another shaft by gearing of any desired velocity ratio.

The point of particular interest to us about this gear is the fact that the equation, regulating the speeds, contains three potentially independent variables, so that it is necessary to know two of them before we can determine the third. For instance if we know A we cannot find B unless we also know C. In the electric case, if we know the primary frequency of an induction motor, for instance, we cannot tell the speed, until we know the secondary frequency also. It will be useful to develop the analogy between a differential gear and an induction motor somewhat further. Let us put:

Primary frequency $= A =$ speed of driver shaft of differential.

Mechanical speed $= B =$ speed of driven shaft of differential.

Secondary frequency $= C =$ speed of intermediate shaft of differential.

We then have: $B = C - A$ in both cases, if we suppose our induction motor has two poles.

So long as C, the intermediate speed or secondary frequency, remains unsettled, we cannot tell what B will be.

We may take a number of suppositions relating to these which are tabulated below:

Electric Case	Mechanical Case.
Secondary open circuited. Machine can deliver no torque, but can run at any speed without opposition, if driven.	*Shaft C free.* B can deliver no torque, but can run at any speed without opposition if driven.
Secondary short circuited through zero resistance. Machine can run at same speed as A and deliver same amount of power as flows into primary.	*C. Fixed.* B runs at the same speed as A, and delivers same amount of power taken in at A.
Secondary, neither open nor short-cuited but closed through a fixed resistance R there being no secondary leakage. Torque is proportional to the secondary current, which is equal to the secondary e.m.f., divided by the resistance. Secondary e.m.f. and, therefore current is proportional to second-	*C. neither fixed nor free but its power output consumed by a brake giving a torque proportional to the speed at which it is driven and consuming power therefore proportional to the square of the speed.* The torque of each of the three shafts must be equal, for multiply the equation $B = C - A$ by the torque T_0 required by the load, and we get: $T_0 B = T_0 C - T_0 A$. This equation can only be con-

ELECTRIC CASE

ary frequency, or say $T_0 = K\ C$ as in the Mechanical case.

Thus we get $B = \frac{T_0}{K} - A$,

exactly the same torque speed characteristic as in the mechanical case.

MECHANICAL CASE

sistent with the conservation of energy, if T_0 is also the torque of the other two shafts.

In this case:

$T_0\ B$ = Output of driven shaft.

$T_0\ C$ = Output of intermediate shaft.

$T_0\ A$ = Input of driver and the equation becomes true.

If we now put:

Torque of intermediate—$T_0 = K\ C$ in accordance with the above assumption, we clearly determine the speeds of all three shafts, for we now have

$$B = \frac{T_0}{K} - A$$

This is the torque speed characteristic of our gear.

According to this analogy, therefore, we may compare any electric machine having a simple harmonic wave of flux to a differential gear, the primary input corresponding to the input of the driver shaft, the mechanical output corresponding to the output of the driven shaft, and the secondary output corresponding to the output of the intermediate shaft.

Hence a set consisting of motor and generator may be compared to two such differential gears coupled together.

Now it is well known that no combination of gearing, however arranged can give us a smooth and gradual speed change, the uttermost possible being a number of steps. Yet certain electric machines do give this gradual speed change, since they embody a device which we have not yet discussed, viz: a commutator. The commutator may be regarded as the only practical gradually adjustable gear in existence.

Consider a commutator fitted with a polyphase arrangement of brushes as in Fig. 2. If polyphase currents of frequency f_1 cycles per sec. are fed in through the terminals $A_1\ A_2\ A_3$ and the commutator revolves with speed S revolutions per sec. the slip rings $B_1\ B_2\ B_3$ which are supposed to be equal in number to the commutator segments, and one being joined to each, will deliver polyphase currents of frequency $f_2 = f_1 \pm S$ according to whether the commutator revolves with or against the direction of rotation of the inflowing current.

Hence for the case of a "two-pole" arrangement of the brushes on the commutator, we have

$$S = \pm (f_1 - f_2)$$

This is particularly obvious if $f_1 = 0$. If, however, the brushes are connected "four-pole" for instance as shown in Fig. 3, so that the slip ring which is connected to a certain segment say, goes through a complete cycle while the commutator turns through 180 deg. instead of 360 deg., the difference between the commutator and slip ring frequencies will be twice as great as before, or $2S = \pm (f_1 - f_2)$.

In general if $\frac{P}{2}$ be the number of pole pairs for which the commutator brushes are joined

$$s \times \frac{P}{2} = \pm (f_1 - f_2)$$

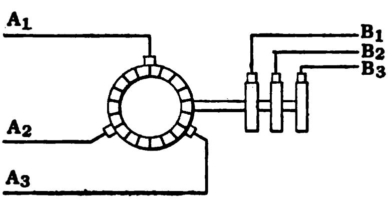

FIG. 2

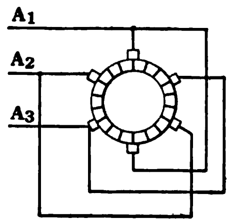

FIG. 3

exactly the same equation as we had for the induction machine. For a two-pole machine $\frac{P}{2} = 1$ and for a four-pole machine $\frac{P}{2} = 2$.

In the commutator frequency converter the whole of the power flowing into the commutator flows out of the slip rings, notwithstanding any change of frequency, whereas, in the electric machine, the power flowing into the primary divides into two parts, one part proportional to S appearing in mechanical form and the other proportional to f_2 appearing as electrical power in the secondary. From considerations of power, this is the outstanding difference between the two cases.

We may now summarize the results we have already obtained.

(1) That motor and generator form together with the transmission line a mechanism in the ordinary sense of word; that is a means of modifying motion and force, or in more general language, of changing the flow of energy.

(2) That the electrical and mechanical speed-torque characteristics of the machine are those of a differential gear, there being a definite relation, $S \times \frac{P}{2} = (f_1 - f_2)$ between the stator and rotor frequency and the mechanical speed which is identical with that in a differential gear. The relation between the mechanical and electrical speeds s, f_1 and f_2, can only be changed by changing the number of poles.

(3) the primary function of the commutator is that of a frequency changer which can change frequencies arbitrarily without change of voltage or power.

(4) The same equation, $S \times \frac{P}{2} = f_1 - f_2$, is also characteristic of the commutator which is a purely electrical differential gear inherently incapable of transmitting a torque.

Hence the different types of electrical machine and systems of electrical transmission may be compared with a number of differential gears, with or without means for varying the number of poles, which corresponds to the velocity ratio of mechanical gear and with or without commutators, which may be regarded as the only practical form at gradually adjustable gear in existence. Other differences which may be noted to exist are as follows:

(5) Systems otherwise identical differ in their method of magnetization.

(6) Several revolving fields may be superposed in the same structure as in the Hunt " internal cascade " machine, the single-phase or elliptic-field machine, or the split-pole converter. Thus the considerations give us three principles of classification.

(1) According to the disposition we make of the secondary power output or output from the "intermediate shaft" of the differential gear. A parallel principle leading to approximately the same result is according to which of the quantities P, f_1, or f_2, is regarded as variable in adjustable speed machines.

(2) According to the manner in which we employ the commutator in our system.

(3) According to the method of magnetization. In addition to this, the machines may be either generators, motors, converters, double current generators, phase advancers etc., but this really introduces no new feature as most machines

are capable of all or most of these functions. If our classification is exhaustive we shall find that when we have assigned our machines a place in each of our classes it is completely defined and nothing further remains to be specified, apart from constructional details. We shall avoid circumlocution if we define the primary as the element into which power flows from the line.

First Principle. Methods of disposing of the secondary power.

The secondary power may be made zero by making the secondary frequency zero or as low as practicable. This is done in almost all the standard types of machines in wide commercial use. Examples of this are the following:

1. Ordinary synchronous machines of all kinds where the secondary frequency is made exactly zero.

2. Induction machines with short circuited rotor where the secondary frequency is made very low, and the small amount of secondary power generated is dissipated as heat.

3. Direct current machines where according to the above definition the armature must be considered as the primary. From our present point of view they only differ from synchronous machines in that the alternating currents which flow in the windings are produced from direct current by the commutator instead of being supplied by the line.

4. Repulsion machines (ordinary and inverted) and in fact all types in which all the windings on one member are short-circuited. How the secondary power in elliptic field machines may be reduced to zero without confining the machine to synchronous speed will be shown below.

Secondary power may be entirely wattless, as in the single phase series machine.

Secondary Power used in another apparatus (*Cascade Systems*). In this case the power flowing out of the secondary is supplied to a second machine which is either independent or mechanically coupled to the first. Examples of this are induction machines cascaded with other induction machines, synchronous machines, or *a-c*, commutator machines.

Secondary power transformed to primary frequency by a commutator and returned to the line. Examples of this are certain types of *a.c.* commutator machines when running at speeds differing from synchronism.

Second Principle. According to the manner of using the commutator.

If we confine ourselves, as we are doing, to a single machine, the only two possible methods of using a commutator are:

(1) On the primary as in the d-c. machine.

(2) On the secondary as in the a-c. commutator machines mentioned above. If, however, as may readily be done, we extend our survey to groups of machines working in conjunction as in cascade sets for instance, a large variety of further interesting methods of application are revealed. A third way of applying it, however, is to confine currents to a definite axis in space as in the repulsion motor etc. This method only applies to elliptic field machines.

Third Principle. Methods of magnetization.

Two distinct methods of magnetization, may be distinguished.

1. The primary may be the seat of the magnetizing currents which may be led in direct from the line as in the normal induction machine and several others. This may be called high-frequency magnetization and involves the appearance of a considerable amount of reactive power proportional to the frequency in the line circuit.

2. The secondary may be the seat of the magnetizing currents which may be led in direct from the line through a frequency changing commutator or supplied by an exciter. This latter method may be called low-frequency magnetization and does not give rise to reactive power in the line. In order to understand the various methods of magnetization better we shall devote further space to the matter later on.

Circular or Constant Intensity Field Machines

To make up a complete circular-field dynamo electric machine we have four elements; the line, the stator, the rotor, and the commutator. By making various combinations of these we obtain different types of machine having different characteristics and adapted to different purposes. Different types of winding exist, each capable of being adapted for connection to direct current, single, or polyphase lines or to a commutator. Each of these is capable of being built for many different polarities. Hence when we say " connect the line to the primary" we therefore assume that it is provided with an appropriate winding. In the following table are shown the

various permutations etc., of the four elements mentioned above which will give rise to practical machines. It will be seen that there are not a very great number.

1. *The Induction Machine.* The simplest is that in which the commutator is entirely absent and the secondary short-circuited, the primary being connected to the single- or poly-phase line and being wound in a suitable manner. In this case the secondary power is very small, being absorbed entirely by the secondary resistance, while the commutator is absent, and the primary winding has two distinct functions to perform, viz., magnetization and the production of a torque. For the former purpose we require a distribution of current density in the stator slots which is in quadrature with the wave of flux density, assumed to be harmonic when we assume a circular field. For the latter purpose the distribution of current density in the stator slots should be in phase with the wave of flux density. Hence two currents, the "magnetizing" and "load" currents, in quadrature with one another, must flow in the stator winding, and this must be of the distributed type in order to allow of its producing an approximate sine wave of magnetism. Such a machine is confined to speeds close to synchronous.

2. *The Synchronous Machine.* The two distinct functions which the stator winding performs in the above machine are separated in the next type which differs from the above solely in that the magnetization is of the low-frequency type and therefore the magnetizing currents on the secondary. Although a distributed primary winding is still used to diminish the leakage etc., yet it is not so essential as in the induction motor, since the primary has no longer to produce the magnetization.

The secondary winding is usually of the concentrated type since it revolves with the flux wave and does not cut it. Under the same heading we must include induction machines in which the secondary is excited by low-frequency currents from what is called a phase advancer. In this case the secondary power is not strictly zero but it is absorbed by secondary resistance.

The function of the phase advancer, which is a small, low-frequency dynamo, is to produce a current in the secondary which is in quadrature with the load current and so capable of producing magnetization. This phase advancer may also be made to supply the secondary I^2R loss whereupon the slip is reduced to zero and the machine becomes synchronous. This case only

differs from that of the ordinary synchronous machine in that the position of the flux wave relative to the secondary, though invariable during running, may be adjusted to have any position instead of being fixed by the construction of the machine.

3. *Polyphase Commutator Machines.* The third type having a commutator on the secondary may be regarded firstly as a mere constructional modification of the induction machine, the advantage of the use of a commutator lying in the greater flexibility attained. In fact it is quite clear that if the squirrel cage rotor mentioned above we substitute a commutator rotor with all the brushes short-circuited no alteration in the characteristics will be produced.

Suppose the commutator rotor to have the same number of turns as the primary. Instead of short circuiting the brushes, suppose the stator to be fitted with a second or neutralizing winding having the same number of turns as the rotor or the primary and connected in series with it in such a manner that the two together form a non-inductive circuit. Thus the commutator rotor is connected into the star of the neutralizing winding on the stator.

Now suppose the polyphase line connected across rotor and neutralizing winding, and let us consider what happens. The rotor voltage is still zero since it is still running in synchronism with the flux, but the same e. m. f. is induced in the neutralizing winding as in the ordinary primary winding since the two may be exact duplicates of one another lying in the same slots.

This e. m. f. therefore balances the primary e. m. f. Since the ampere turns of the rotor and neutralizing winding are exactly equal and opposite they exert no inductive effect on the original primary winding and it is therefore relieved of all currents except magnetizing currents and its section may be proportionately diminished.

So far we have achieved nothing but a constructional modification of the induction machine but we now begin to see how this construction may be turned to advantage.

As soon as we depart from synchronism, an e. m. f. appears across the commutator brushes which, multiplied by the current, is a measure of the secondary power. Owing to the presence of the commutator, this secondary power always appears at line frequency and is absorbed direct from the line above synchronism and returned direct to it below. Hence such machines are capable of giving adjustable speed operation whether connected shunt or series, and this is their chief claim to existence.

4. *The Direct-Current Machines.* The fourth modification of the fundamental induction machine is that in which the commutator is interposed between the line and the primary winding and consequently the primary receives a frequency different from that of the line. The most prominent example of this class is the direct-current machine in which a wave of current density revolving relative to the primary of the machine is produced from the d-c. supply by the commutator. The magnetization which may be shunt or series is of the low-frequency type derived direct from the line and of course the secondary power zero. Since the primary frequency is due only to the rotation of the machine, the machine must always notwithstanding its adjustable speed be of the synchronous type. If a machine of type 3 be run very much above synchronism the secondary power will be much greater than the primary, and it will gradually approach the fourth class which is the limit towards which the third class approaches as the frequency tends to zero. All those exciters, phase advancers, etc. adapted to deal with currents of slip frequency must be placed in this fourth class, though the distinction between the third and fourth class will be more in the frequency of supply relative to that of rotation than otherwise. In the accompanying table have been written down the various permutations of the different alternatives contained in our four classes excluding those which are obviously self contradictory. It will be seen that there are not a very great number of permutations and of these some are impossible or at least unknown while some are merely special cases of others, occurring only at a particular speed (synchronism). Thus, finally, of all the possible permutations, only four distinct types of machine emerge—those briefly described above, all of which may be derived from one another by simple mechanical processes of inversion, etc. Thus starting from the d-c. machine we may (1) replace the commutator by a polyphase set of collector rings and we have a synchronous machine (2) replace the field winding by a squirrel cage and we have the induction type (3) invert, making the secondary the rotor, replace the squirrel cage by a commutator carrying a polyphase set of short-circuited brushes and reconnect the brushes in the manner described above and we have the polyphase commutator type. These constructional modifications have one of two objects,

(a) Adaptation to different kinds of current as when we change a direct-current to a polyphase machine.

(b) To obtain characteristics adapted to some particular variety of industrial work as when we change the induction to the commutator type. It should be recognized however, that,

CIRCULAR OR CONSTANT INTENSITY FIELD MACHINES

Name	Disposition of secondary power	Commutator	Magnetization	Shunt or series	Remarks
1.	Zero or absorbed by secondary resistance	absent	H.F.	Series	Impossible or unknown
2. Induction machine.........		"	"	Shunt	
3.		"	L.F.	Series	Impossible or unknown
4. Synchronous machine.........		"	"	Shunt	
5.	"	on primary	H.F.	Series	
6.	"	"	"	Shunt	
7. D.c. series mach.	"	"	L.F.	Series	
8. D.c. shunt mach.	"	"	"	Shunt	
9. Polyphase commutator series mach..........	"	on secondary	H.F.	Series	The secondary power is only zero at synchronism so these machines are only special cases of the next four
10. do. shunt........	"	"	"	Shunt	
11. do. series compensated......	"	"	L.F.	Series	
12. do shunt.......	"	"	"	Shunt	
13. Comm. series mach..........	Returned through Commutator	on secondary	H.F.	Series	
14. Do. shunt......		"	"	Shunt	
15. Do. series compensated......	"	"	L.F.	Series	
16. Do. shunt........			"	Shunt	
17. Induction mach.	Used in separate apparatus	absent	H.F.	Series	
18. Cascaded with	"	"	"	Shunt	
19. 13, 14, 15 or 16	"	"	"	Series	
20.	"	"	"	Shunt	
		CONVERTERS			
Induction	Absorbed by secondary resistance	on primary	H.F.	Shunt	
Synchronous	Zero	"	L.F.	"	
Commutating frequency	Wattless	"	H.F.	"	
converter	"	"	L.F.	"	

NOTE: " H.F. " is an abbreviation for " high-frequency " and " L.F. " for low-frequency.

in spite of all variations, there is but one dynamo electric machine retaining its main features unchanged throughout. It is interesting to note that machines with series characteristics invariably have commutators.

CONVERTERS

Various types of converters exist calling for a place in our classification. The function of a converter is essentially to produce a change in frequency and hence when it consists only of a single machine it is invariably of the commutator type. Such an apparatus (in the ideal case) is not called upon to develop torque and hence no secondary power exists. Certain types of frequency converter are fitted with field windings whose sole purpose is to produce a flux. In this case the secondary power is wattless or reactive, the only possible case of reactive secondary power in a circular field machine. Converters to operate on constant voltage must necessarily be shunt machines.

ELLIPTIC FIELD MACHINES

When we come to elliptic field machines an entirely new set of possibilities presents itself. The secondary power in such a machine may be reduced to zero though neither the secondary e.m.f. nor current are zero. Moreover in certain cases it may become entirely wattless a case which cannot occur in circular field machines. An elliptic field machine must necessarily have a commutator, since any machine having a short-circuited or separately-excited secondary must necessarily give rise to circular field. Owing to the present of this commutator the secondary power when it exists appears at line frequency, and there is therefore no difficulty in returning it to the line or deriving it therefrom. In dealing with circular field machines we found it useful to draw a distinction between the cases in which the commutator was on the primary or on the secondary and we shall still find it useful to draw the same distinction. It enables us to divide our machines into two classes containing pairs of machines which may be shown to be exactly reciprocal to one another. For instance dealing with single-phase series type motors we may divide them into a number of pairs as follows:

Name	Commutator	Field	Secondary coil	Primary coil
Neutralized Series }	Primary	Stator	Stator	Rotor
Compensated Repulsion }	Secondary	Rotor	Rotor	Stator
Inverted Repulsion }	Primary	Rotor	Stator	Rotor
Ordinary }	Secondary	Stator	Rotor	Stator
Induction Series }	Secondary	Stator	Rotor	Stator
Comp. Inverted }	Primary	Rotor	Stator	Rotor
Repulsion Motor }				

Diagrams of these machines are shown in Figs. 4, 5, 6, 7, 8 and 9. The last machine which I have provisionally called the compensated inverted repulsion motor is shown in Fig. 9. It has never been discussed as far as I am aware yet it is quite as practical a type as any of the others and may even have some advantages. Let us now consider in what manner the secondary power

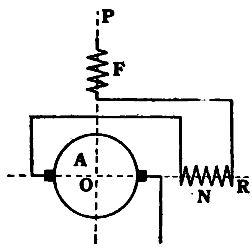

FIG. 4

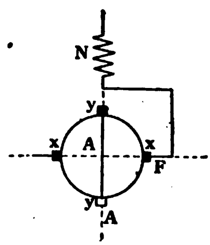

FIG. 5

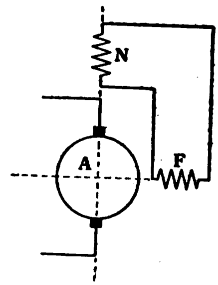

FIG. 6

is disposed of in some of these pairs of machines. In the repulsion motors, ordinary and inverted, the secondary circuits are completely short circuited and hence the secondary power zero. In the neutralized series and compensated repulsion motors, as also in the last pair, the secondary power is used entirely for magnetizing and is therefore wattless. If the magnetization

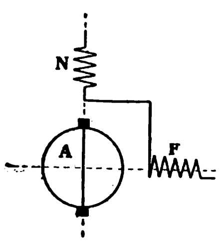

FIG. 7

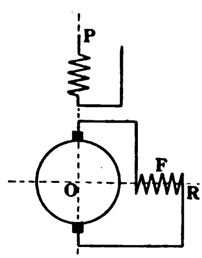

FIG. 8

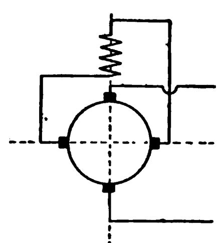

FIG. 9

is of the low-frequency type, as in the compensated repulsion motor, the secondary power* vanishes completely at a particular speed (synchronism). The distinction which we have drawn between machines having the commutator on the primary and on

*It should perhaps be mentioned that by "secondary power" we mean the actual power measurable by a wattmeter and not any fictitious quantity such as some theories accustom us to consider.

the secondary merely symbolizes other important differences. Machines with commutator on the primary are "pulsating field machines" having a field distribution of the well known type characteristics of the neutralized series motor, viz., having a definite axis fixed in space. Such machines may conveniently be built with salient poles. Machines with commutator on the secondary are "revolving field machines" in which the field revolves elliptically at all speeds, becoming circular, as a rule, at synchronism. Such machines require an induction motor type of stator with uniform air gap all around. There are moreover important differences between the commutation of the two types. In the "revolving field type," since the flux revolves with the armature at synchronism, the commutating conditions are identical at this speed with those in direct-current machines. In the "pulsating field type" of course no such conditions exist, hence the above mentioned distinction symbolizes a large number of practical differences independent of any theory. Moreover the same distinction has been shown to be significant with reference to all standard types of machine also. In order to discuss the elliptic field machines more fully it is necessary to enter upon their theory to a certain extent. The writer has accustomed himself to think in terms of a certain theory which is described in a treatise entitled "Single Phase Commutator Motors" published by him in 1913. Although this method of studying elliptic field motors is not at present very widely known it presents considerable advantages, and it will accordingly be made use of here. The purpose of the following discussion, however, is purely that of explaining the two reciprocal classes of single phase series type motor which have been mentioned above, and as adds nothing further to our results may be omitted by the reader who is unfamiliar with the methods used, and who is willing to take for granted the reciprocity of the two classes.

Power Calculations in Elliptic Field Machines

The secondary power is now the product of an elliptically distributed e.m.f. and an independent elliptically distributed current which may have quite different axes from that of the e.m.f. The multiplication of such ellipsis has been discussed in the writers "Single-Phase Commutator Motors," Appendix, p. 108-109 where two products, the "sine" and the "cosine" product are defined as follows: Suppose we wish to multiply any two vector ellipses we must resolve each into a pair of conjugate

diameters which will be in quadrature with one another. These are shown in Fig. 10 as ab and $a'b'$ and they must be so chosen that a is in phase with a' and b with b'. If α is the angle between a and a' and β that between b and b' we define the "cosine" products of the two ellipses as $a\,a' \cos\alpha + b\,b' \cos\beta$. If one ellipse represents a current distribution and the other an e.m.f. distribution, then " cosine " product represents the maximum power flowing due to the two, and $\frac{1}{2}(a\,a' \cos\alpha + b\,b' \cos\beta)$ is the mean power. In the case, in which both ellipses reduce to circles, we have $a = b$, $a' = b'$ $\alpha = \beta$ so that the mean power will be $a\,a' \cos\alpha$ which is the usual expression. Since a is in quadrature with b' and b with a' we have not considered the products of these terms as they will give rise to purely wattless or reactive terms. It is quite clear that the above expression may be reduced to zero in many ways without either of the fac-

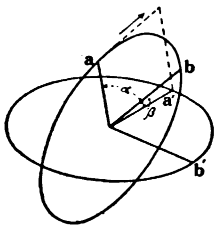

FIG. 10

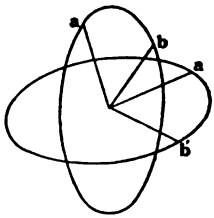

FIG. 11

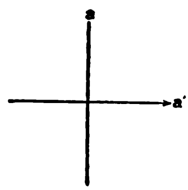

FIG. 12

tors being zero and hence the secondary power of our elliptic field machines may be zero or purely wattless without either the secondary current or e.m.f. being zero. Hence, such machines are not restricted to synchronous speed in the absence of some means of disposing of the secondary power as are machines of the circular field type. We shall now discuss some of the principal cases in which such a product may be zero without either of the factors vanishing.

1. Ellipses similar and of similar phase and at right angles to one another (see Fig. 11). In this case $\alpha = \beta = 90$ deg. and the product is wattless since neither $a\,b'$ nor $a'b$ are at right angles.

2. Each ellipse reduces to a straight line both being at right angles (see Fig. 12). In this case the product is accurately zero, not wattless, and this is the only case in which it is accurately zero except with a circular field at synchronism

$$a\,a' \cos\alpha = -b\,b' \cos\beta$$

In this case the two ellipses rotate in opposite directions. We shall not come across any instance of this. Let us now consider what distributions of current and e.m.f. occur in some of the best known types of single-phase motor having series characteristics. Consider first the case in which the commutator is on the primary. This case includes two well known types the neutralized series motor and the inverted repulsion motor. Both of these involve a stator element which is or permissibly may be short circuited.

1. Taking the inverted repulsion motor first: In the stator or secondary element the current flows entirely in the short circuited coil and will be represented by a straight line ellipse parallel to the axis of that coil. Since the coil is short circuited the flux cannnot interlink it and must be therefore of the "pulsating" type represented by a straight line ellipse perpendicular to the axis of the coil. The same ellipse may

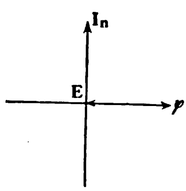

FIG. 13

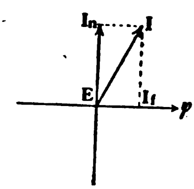

FIG. 14

also represent the e.m.f. to a suitable scale if we displace the phase by 90 deg. Hence, in this case, the two ellipses of e.m.f. and current reduce to two straight lines at right angles and the "cosine" product is therefore accurately zero (see Fig. 13). The ampere turns necessary to excite the flux, are of course supplied by the primary.

2. *The Neutralized Series Motor* also contains a short circuited element on its stator or secondary, viz., the neutralizing coil. For the same reasons as stated above, the current I_n in the neutralizing coil and the flux and e.m.f. will be represented by two straight line ellipses at right angles (see Fig. 14). In the present machine, however, the magnetizing ampere turns necessary to excite the flux are on the secondary, being supplied by the field winding. The field currents will be represented by another straight line ellipse I_f parallel to φ and the resultant stator current by I. Thus since I and E are no longer at right angles their product will not be accurately zero but since they

are still in quadrature it will be wattless. We shall now turn to the machines of the "rotating field" type which are reciprocal to the two just discussed, viz., the ordinary and compensated repulsion motors.

3. *The Repulsion Motor.* In the rotor or secondary element the current flows entirely in the short circuited circuit and will be represented by a straight line ellipse parallel to the axis of that circuit. The e.m.f. across any short circuited circuit is obviously zero, and the e.m.f. ellipse therefore reduces to a straight line perpendicular to the first, though of course it no longer follows that the flux is of the same form. Thus the rotor e.m.f. and current ellipses of the ordinary repulsion motor are identical with the stator e.m.f. and current ellipses of the inverted repulsion motor (see Fig. 15).

4. *The Compensated Repulsion Motor* also contains a short circuited element on its rotor or secondary. For the same reasons as in the ordinary repulsion motor, the current in the

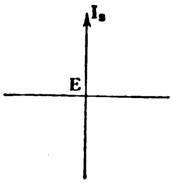

FIG. 15

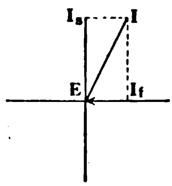

FIG. 16

short circuit I and the e.m.f. will be represented by two straight line ellipses at right angles (see Fig. 16). In this machine however the magnetizing ampere turns necessary to excite the flux are on the secondary, being supplied by the circuit through the field brushes. The field currents will be represented by another straight line ellipse I_f parallel to E and the resultant stator current by I. Thus since I and E are no longer at right angles their product will no longer be accurately zero, but since they are still in quadrature it will be wattless (reducing to zero at synchronism, however, since in this machine low-frequency magnetization is made use of). In the above discussion only the secondary e.m.f. and current distributions are considered but it is easy to show that primary e.m.f. and current distributions are reciprocal also. In order to bring this out in its clearest form we may paraphrase the discussion in "Single Phase Commutator Motors" pp. 51, 52, 53, in two parallel columns:

The Repulsion Motor Rotor E.M.F. Since the rotor is short circuited along the axis $O\ P$ there can be no e.m.f. along that axis and the rotor e.m.f. ellipse is therefore a straight line along $O\ R$ perpendicular to $O\ P$.	*The Inverted Repulsion Motor Stator E.M.F.* Since the stator is short circuited along the axis $O\ P$ there can be no e.m.f. along that axis and the stator e.m.f. ellipse is therefore a straight line along $O\ R$ perpendicular to $O\ P$.
Flux Distribution. Such a rotor e.m.f. distribution can only be produced at speed K by a flux ellipse whose axes lie along $O\ P$, and $O\ R$, that along $O\ R$ being of length a say that along $O\ P$ being Ka where K = speed synchronism. In this case the "Transformer" e.m.f. and e.m.f. of rotation along the short circuited axis $O\ P$ will cancel leaving a straight line distribution of rotor e.m.f.	*Flux Distribution.* Such a stator e.m.f. distribution can only be produced by an exactly similar flux distribution which may be represented to an appropriate scale by exactly the same straight line ellipse.
Stator E.M.F. The stator e.m.f. due to this flux distribution will also be represented to a suitable scale by exactly the same ellipse as the flux.	*Rotor E.M.F.* This purely single-phase flux ellipse induces in the rotor an e.m.f. ellipse whose axis lie along $O\ P$ and $O\ R$, that along $O\ R$ being of length a say, and that along $O\ P$ being Ka.
Terminal E.M.F. This ellipse must touch a line perpendicular to $O\ Q$ and at a distance OE from the origin equal to the maximum terminal e.m.f.	*Terminal E.M.F.* This ellipse must touch a line perpendicular to $O\ Q$ and at a distance $O\ E$ from the origin equal to the maximum terminal e.m.f.

Shunt Type Machines

There is by no means so large a variety of shunt type as of series type motors having different modes of operation though substantially the same characteristics. Although the number of constructional modifications which may be suggested is, of course, endless, all practicable types of motor reduce, in the end, to what is essentially one machine. This is due to the following facts.

Consider the ordinary shunt motor operated on alternating current. If the armature current is approximately in phase with the line e.m.f., which it should be, of course, for operation on good power factor, it will be in quadrature with the flux which lags 90 deg. behind the line e.m.f. In order therefor

to keep the flux and current in phase we need to supply the field with an e.m.f. leading 90 deg. on the armature or line e.m.f.

There is but one way to generate such an e.m.f., if we are to retain a purely single phase motor, and that is by means of a pair of brushes arranged on the armature at right angles to the load brushes or those which carry the main current. The practical machine in which this principle is carried out in

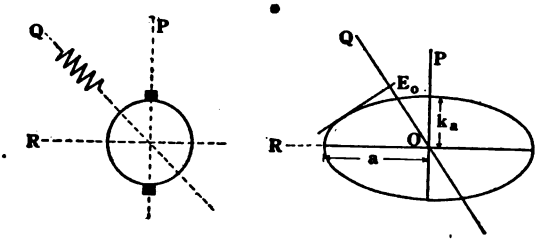

FIG. 17

its simplest form is usually called the Atkinson commutator induction motor (see Fig. 16). It consists of a distributed single-phase winding on the stator, a pair of short circuited brushes co-axial with the stator winding, and another pair at right angles thereto also short circuited.

The e.m.f. of rotation induced in this latter pair of brushes by the primary flux leads 90 deg. on the line e.m.f. and is

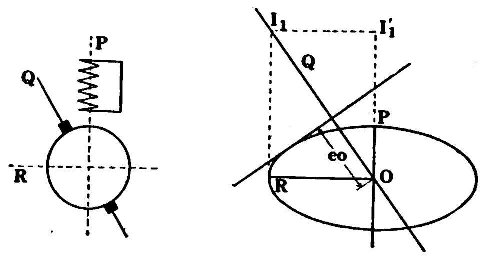

FIG. 18

therefore capable of producing the field we require. This commutator armature with its two pairs of short circuited brushes may be replaced by a plain squirrel-cage armature giving us the ordinary single-phase induction motor. Such a machine is of the "rotating field" type and is therefore capable of low frequency magnetization, otherwise known as compensation, by a well known method. Such a machine is the single phase

representative of the polyphase or circular field machines discussed above, and in fact, a polyphase commutator machine of which one phase has been disconnected will if of the shunt type continue to operate on single phase just as an induction motor will. Our principles of classification do not necessitate any distinction being drawn between single phase and polyphase machines so long as the fields of both remain circular. The principle utility of these single-phase commutator shunt machines is as adjustable speed machines and two methods exist for varying the speed from synchronous:

1. By introducing power into the appropriate rotor circuit (see Fig. 19) by means of a transformer in exactly the same way as in the case of three-phase motors. Our principles as

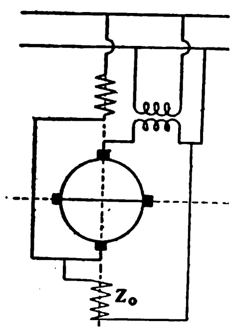

FIG. 19

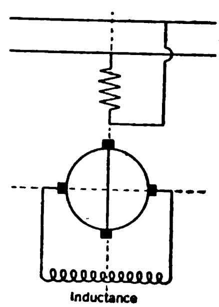

FIG. 20

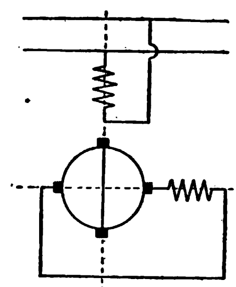

FIG. 21

mentioned above do not necessitate a distinction being drawn between the single- and the three-phase case.

2. A method peculiar to the single-phase motor, consisting in weakening the field perpendicular to the stator axis by means of reactance or an auxiliary coil placed in series with the field brushes. In this case the rotor power is no longer zero but wattless, being that consumed by the reactance or by the auxiliary coil. This method of weakening the field is shown in Figs. 20 and 21.

SUMMARY

We may now summarize the results of our discussion and make some final suggestions as to the best methods of classification.

1. The classification to which we have been led by the above discussion first of all subdivides our machines into

(*A*) circular field or constant intensity field machines including all direct-current and balanced polyphase machines, all the standard types in fact.

(*B*) Elliptic or variable intensity field machines including single phase and unbalanced polyphase apparatus.

(*C*) Multiple polarity apparatus such as the Hunt, internal cascade machine and the split pole converter whose operation depends on the presence of harmonics in the main field. No detailed discussion of this class is attempted.

(*D*) We may regard homopolar machines as a fourth class.

2. It is shown from general mechanical considerations that electric power is developed in both the primary and secondary element of the general induction machine which is taken as typical, and that before an operable machine can be produced some method of disposing of this secondary power must be decided on. Various methods by which it may be reduced to zero, as is done in all standard machines are discussed. Other methods of disposing of it are by its utilization on a separate apparatus (cascade sets) by commutator frequency transformation and returning to the line (some commutator machines), or by rendering it purely reactive. This can be done in elliptic field machines only.

3. A second important difference depends on the use to be made of the commutator which may be absent, on the primary, or on the secondary. Except in d-c. machines the commutator is only useful for obtaining adjustable speed.

4. A third difference, not so important as the above two, depends on the method of magnetization. Two different methods of magnetization are distinguished, viz., "high frequency" magnetization leading to the appearance of considerable reactive power on the line, as in the ordinary induction motor, and "low frequency," as in the synchronous and compensated types.

5. Lastly, many types may be connected either series or shunt.

6. A table is constructed showing all possible combinations of these five sets of alternatives, and it is shown that they cover all known types of "constant intensity field" machines and that when the place of any apparatus in the table is assigned it can only be constucted in one way.

7. Coming to the elliptic field machines we find that the secondary power can be reduced to zero or a purely wattless form in many ways without either secondary current or e.m.f. being zero.

8. Our second principle of classification according to whether the commutator is on the primary or secondary leads us to distinguish elliptic field series type machines into two classes "pulsating field" machines—the neutralized series motor and the inverted repulsion motor and "elliptically rotating field" machines—the ordinary and compensated repulsion motor, etc. It is shown that a certain reciprocity or duality exists between these types whereby stator e.m.f. and current distribution on the one type is exactly the same as rotor e.m.f. and current on the other. The two types are distinguished by different constructional features, salient poles in the one type and uniform air gap in the other, and by differences in commutation.

9. Shunt type machines when purely single phase are invariably of the rotating field type as there is only one way of producing the requisite shunt field.

10. Finally a table may be constructed by reference to which a characterization of any dynamo electric machine may be carried out.

Type of field	Disposition of Sec. Power (A)	Commutator	Magetization	Series or Shunt
Constant Intensity (C)	Zero (1)	None (N)		
Variable Intensity (V).		On Primary (P)		
	Wattles (2)			
Multiple Polarity (M).	In Cascade (3)	On Secondary (S)	High. Fre. (H)	Series (Se)
	Returned to			
Homoploar (H)	line by Trans(4)		Low Fre. (L)	Shunt (Sh)

From this table a machine may be characterized, as for instance: $C—A1—P—L—Se$ would be the direct-current series machine, or $V—A1—P—H—Se$ the repulsion motor. "Some possible combinations of lettering will be found self-contradictory. The principal test which we can apply to our system is to ascertain whether an apparatus can be denoted quite unambiguously by this lettering or whether several kinds of apparatus having legitimate claim to be regarded as different, and not as mere constructional modifications of one another, are denoted by the same lettering. The writer has tested it in this way to a certain extent, but an independent critic might be able to reveal difficulties not at present apparent. Of course, the present paper does not pretend to be more than a step in the direction of classification and some modification of the present, or an entirely different scheme, might be found necessary.

Presented at the meeting of the Baltimore Section, A. I. E. E., February 26th, 1915, and to be discussed at the 32d Annual Convention, A. I. E. E., Deer Park, Md., June 28, 1915.

FOUR YEARS' OPERATING EXPERIENCE ON A HIGH-TENSION TRANSMISSION LINE

BY A. BANG

ABSTRACT OF PAPER

The Pennsylvania Water and Power Company, since it started operation of its hydroelectric plant at Holtwood, Pennsylvania, has kept a careful record of all operating events. In the following paper this record is given for the four years 1911-1914, as far as the *high-tension transmission line*, Holtwood to Baltimore, is concerned. The record deals essentially with certain observations made on lightning flash-overs, deterioration of insulators, sleet on cables, and the various means adopted to prevent disturbances to operation from these causes.

THE TRANSMISSION line for which the operating record is given herein is the line which transmits energy at 70,000 volts from the Pennsylvania Water and Power Company's hydroelectric plant on the Susquehanna River at Holtwood, to the same company's terminal station at Baltimore, Md., where the current is stepped down for distribution purposes. Practically all the load consists of synchronous machinery, such as synchronous converters, frequency changers, etc.

This line is about 40 miles long and runs mainly in the direction north-south, through a hilly country, on a right-of-way 100 ft. wide. It consists now of two rows of steel towers, each capable of carrying two independent three-wire circuits. The first of these tower lines (No. 12) was built in 1910, with both circuits installed; the second (No. 56) in the summer of 1914. On this latter at present only one circuit is installed (circuit No. 6).

There is a considerable number of differences in the design of the two lines. The following is mainly a description of the new line, though wherever there is an essential difference, it is pointed out.

Towers. The towers are galvanized steel towers, designed for six power cables and two ground cables (on the old line only one

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ground cable); they are spaced about ten to a mile and the cables on the new line are anchored at every fifth tower at least. All the towers on the new line are set in concrete foundations, while on the older line, steel tripod foundation stubs were used for the suspension towers.

The height of the tower is 44 ft., from ground to the lower crossarm. Ten and twenty ft. extensions have been used to increase the height of the towers whenever needed. The distance between the crossarms is 9 ft., against 7 ft. on the older tower line, and the ground wires are located 4½ ft. above the upper crossarm. Contrary to what was the case on Line No. 12, where the power cables for each circuit were located all three in a

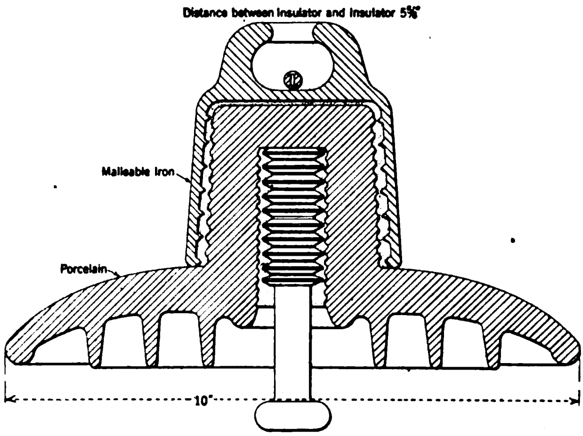

FIG. 3—TYPE OF INSULATOR USED ON CIRCUITS NOS. 1 AND 2, HOLTWOOD–BALTIMORE TRANSMISSION LINE

vertical line one above the other, the cables on the new line have been staggered, so that the ground wire crossarm and the middle crossarm are the longest (each 23 ft. from tip to tip). The upper crossarm is 15 ft. and the lower 17 ft. 6 in. This has been done to prevent trouble from sleet.

Conductors. The conductors are 300,000-cir. mil, 19-strand aluminum cable.

The ground wires consist of ⅜-in. galvanized seven-strand steel cable.

Calculated Load. Maximum load on the cables is assumed to occur at a temperature of 25 deg. cent., with a wind pressure of 15 lb. per sq. in. on wires covered with ½ in. of sleet. During

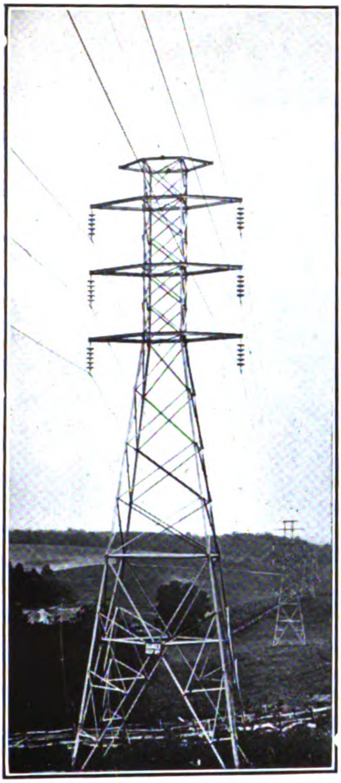

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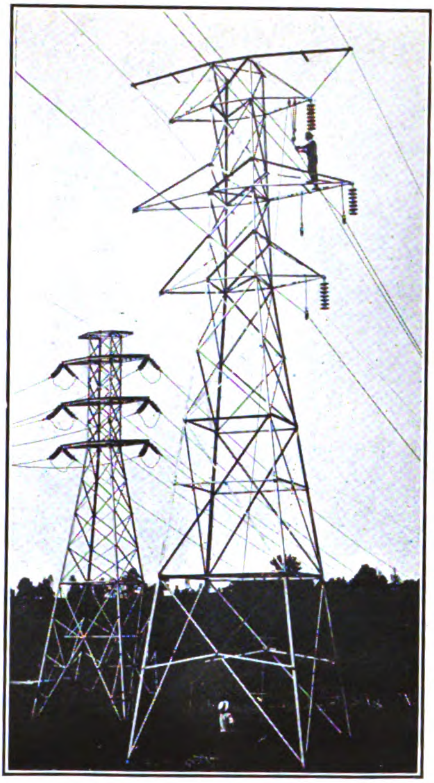
FIG. 1—SUSPENSION TOWER ON LINE 12—HOLTWOOD—BALTIMORE



[BANG]

FIG. 2—SUSPENSION TOWER ON LINE 56—HOLTWOOD-BALTIMORE—IN THE BACKGROUND: STRAIN TOWER OF THE OLDER LINE NO. 12

[BANG]

FIG. 5—STRING OF SUSPENSION INSULATORS FOR LINE 56

[BANG]

FIG. 6—PARTIAL INTERRUPTION NO. 12, 1913. INSULATOR REMOVED FROM TOWER NO. 128, BOTTOM PHASE, CIRCUIT NO. 2 SUSPENSION TYPE

these load conditions the tension in the cables approaches the elastic limit.

The stringing tension at + 25 deg. cent., was 500 lb. for the power cables and 950 lb. for the ground cables.

Insulators. The insulators are of the suspension disk type, 10 in. in diameter. The units selected for the newer line have the following electrical characteristics:

Individual dry flash-over voltage	=	95,000 volts.
Individual puncture voltage	=	140,000 to 150,000 volts.
Units on older line have a dry		
flash-over	=	90,000 volts.
and puncture	=	100,000 to 107,000 volts.

Eight units to the string are used on anchor towers and seven on suspension towers. Seven units correspond to a dry flash-over voltage of 378,000 volts.

On the old line originally, five and six units, respectively, were used for suspension and strain towers.

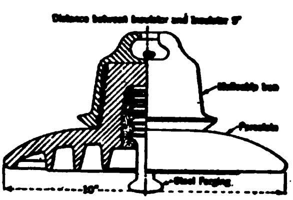


FIG. 4—SHOWING TYPE OF INSULATOR USED ON CIRCUITS NOS. 5 AND 6

The new tower line is built parallel to line No. 12, distance between lines being only 50 ft. on centers. On account of this it was necessary to place the towers on the new line as nearly as possible opposite the towers on the old line. The number of anchor towers has been increased on the new line in order to prevent longitudinal vibrations and to lessen the chances of sleet trouble.

The standard span is 500 ft., the shortest span is 125 ft., and the longest built with standard towers and cables is 1080 ft. All spans of 800 ft., or more are anchored at both ends. Double strings of insulators are used at all railroad crossings. The elevation of the line varies from about 600 ft. above sea level at the generating end to about 50 ft. at the receiving end.

Electrical Data.

Frequ		25 cycles.
Normal line voltage between phases		60,000 to 70,000 volts.
Ohmic resistance of one wire.....	=	12.1 ohms (12 deg. cent.)
Ohmic reactance at 25 cycles is..	=	13.1 ohms
Impedance at 25 cycles is........	=	17.9 ohms

Losses in three lines at 200 amperes........................ = 5800 kw. or 10 per cent when 58,000 kw. are transmitted.

Capacity current.............. = 3.5 amperes per wire.

Operating Record

Below is given a tabulation of all the disturbances to normal operation of the system originating in the transmission lines, together with the cause of the trouble and the year it occurred. These disturbances have further been divided into three groups, depending on their seriousness, *i. e.*, total interruptions (T.I.), where all the load was lost, though generally not more than for a few minutes; partial interruptions (P.I.), where a percentage of the load was momentarily lost; and, finally, mere voltage or frequency disturbances (V.D.), where no load whatever was lost. These disturbances have been recorded whenever the voltage changed suddenly five per cent or more.

TABLE I.—OPERATING RECORD FOR HOLTWOOD-BALTIMORE TRANSMISSION LINE, JANUARY 1, 1911, to DECEMBER 31, 1914

Cause	1911			1912			1913			1914			Total for four years		
	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.
Lightning.......	23	..	10	3	19	4	3	17	11	1	6	7	30	42	32
Defective insulators..........	..	..	..	..	..	..	1	..	..	..	1	1	1	1	1
Sleet on cables....	..	..	..	..	..	..	..	..	..	2	2	.	2	2	..
Birds on line.....	1	..	..	..	..	..	1	..	2	1	3	2	3	3	4
Wires blowing together.........	..	..	..	..	..	..	..	..	..	..	..	1	..	..	1

It will be seen that the cause for all the disturbances can be covered under the five headings: lightning, defective insulators, sleet on cables, birds on line, and wires blowing together.

Of these the overwhelming cause of trouble is lightning.

It may be of interest to recount a few observations made on the effect lightning has on a transmission line in operation.

Though the lines are protected at both ends with aluminum lightning arresters, which duly discharge during storms, lightning

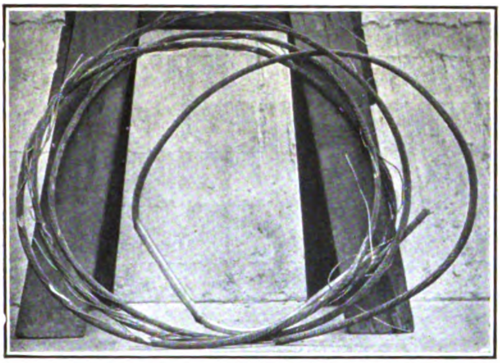
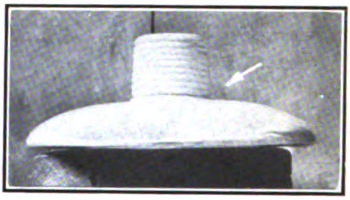


FIG. 7 [BANG]

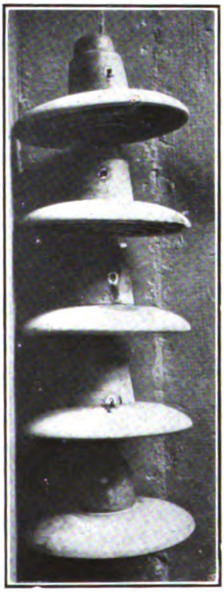


[BANG]

FIG. 12—REMOVED FROM STRAIN TOWER NO. 163, 40,000 OHMS BETWEEN CAP AND PIN—BROKE DOWN AT 21,750 VOLTS—CRACK AT THE BOTTOM OF THE CAP

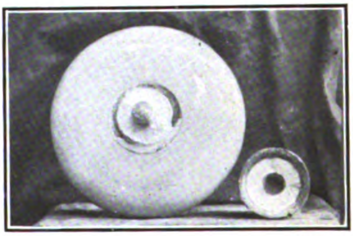
[BANG]

FIG. 10—INSULATOR STRING PUNCTURED ON LINE



[BANG]

FIG. 11—INSULATOR STRING PUNCTURED BY TEST



[BANG]

FIG. 13—INSULATOR PULLED APART REMOVED FROM STRAIN TOWER NO. 34 CIRCUIT NO. 1, UNIT NO. 3 MIDDLE NORTH READ 50,000 OHMS

[BANG]

FIG. 14—TURKEY-BUZZARD KILLED ON LINE. NOTE SPECIALLY THAT LEFT WING IS BURNED.

Dimensions—Tip of wing to tip of wing 65 in.—tip of wing to toe 34 in.—toe to beak 22½ in.

discharges or surges will nevertheless give rise to "flash-overs" on the line, which, once established, are maintained by the power from the generators. Such flash-overs practically always start at the towers where the clearance distances to ground (*i. e.*, towers) are the smallest (a double or triple ground to the same tower is naturally in effect the same as a two- and three-wire short-circuit). The path of the flash-over may vary. Thus, when circuits Nos. 1 and 2 originally went into service, the suspension towers were equipped with five units to the string and strain towers with six units. With this arrangement it was always found that the flash-over would occur upwards from the conductor, *alongside* the string of insulators.

Fig. 6 shows a typical string of insulators, damaged by such an arc. It can be seen how the three lower insulators are completely broken to pieces, probably mainly due to the heat generated by the arc; the bottom bolt shows a deep burn. It can also be seen from the marks on the string how the arc in this string, instead of traveling all the way from conductor to the tower in one unbroken arc, has broken into small individual arcs, each encircling one insulator. That happens frequently, though not always.

Not only the insulators but also the cable is liable to be damaged by lightning arcs; Fig. 7 shows a typical case. If the arc stayed at one place it would quickly burn the cable through. Fortunately, the arc is generally on the move. As a rule it is blown away from the power house, due to its own magnetic action. On the Baltimore transmission line we therefore generally find the cable damage to the south of the towers; traveling this way the arc burns and pits the cable in spots. In a few seconds the arc may travel five to thirty feet.

When it was found in the first lightning season (1911) that practically all flash-overs occurred along the insulators, the plan was tried in 1912 of increasing the number of disks of a suspension string to seven and of a dead-end tower to eight, on two particular stretches where the lightning had been especially severe. This proved successful in so far that only one lightning stroke occurred on these stretches in 1912 against 22 in 1911. Before the lightning season of 1913 one whole circuit (No. 1) was therefore equipped in this way with seven suspension and eight strain units. The result was, as shown by the power house ground chart record, that in 1913 the lightning flash-overs were distributed between the two circuits as follows:

27 lightning strokes on circuit No. 1.
20 " " " " " 2.
6 " " unknown on which circuit.

In other words, the circuit with the many insulators showed the larger number of lightning strokes. Evidence from inspection of the line showed, however, that whenever the flash-over took place on a suspension tower (which generally was the case in preference to a strain tower) the lightning arc on No. 2 circuit with the five insulators in the string, would as usual rise upwards along the insulator strings to the crossarm above, while on No. 1 circuit with the seven units in the string the arc would in every case go just the opposite way, *i. e.*, from the conductor to the crossarm below (see Fig. 8). This was naturally due to the fact that this clearance distance for the two upper conductors was materially decreased (from about 36 in. to 24 in.) by adding two more units to the string. For the bottom conductor, where the clearance distance still remained ample, the number of flash-overs was greatly reduced. This change in the location of the arc resulted in two distinct gains. In the first place, the arc did not have nearly the same chance for damaging the insulators by heat, as it did not pass alongside them but away from them. The insulator record for 1913 showed this clearly. Thus it was necessary to remove 210 insulators from circuit No. 2, due to lightning damage, and only three from No. 1 circuit. The other advantage gained was that it proved to be easier to extinguish the arcs on No. 1 circuit and that it could be done with much less loss of the synchronous load connected to the system (on account of the preponderance of two-wire short circuits compared with three-wire short circuits). The following year one more unit was added to No. 2 circuit suspension towers and two more to the strain towers, and this is the way it is at present.

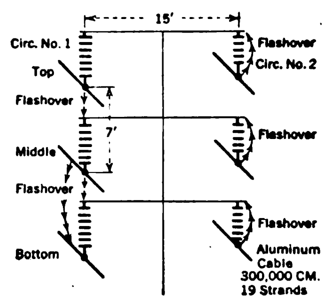


FIG. 8—DIFFERENT PATHS TAKEN BY LIGHTNING FLASH-OVERS

Altogether the number of insulators removed from the line due to lightning damage is small, not more than about one hundred per year, on the average, and the number is not on the increase.

Far more important from a maintenance point of view is the

continuous *deterioration* of the porcelain in the insulators, such as it was discovered a few years ago could be determined on insulators of the suspension type by means of taking insulation readings between the pin and cap (megger tests).

The Pennsylvania Water and Power Company began investigations by this method in the autumn of 1913. The megger used was a 1000-volt instrument with a range from 10 to 2000 megohms. The result was rather surprising. While the majority of insulators, when the weather was dry enough to permit of any testing, naturally would read infinity, many were found which would read below the scale of the instrument, *i. e.*, below 10 megohms. When these were tested later on with a lower-reading megger, many of them would read even below ½ megohm or lower. On none of them could any external damage be seen. To all outside appearances they were perfectly good insulators and still their insulation value was gone.

The first complete test of circuits Nos. 1 and 2 was made in the winter 1913-1914, after about three years of operation. Counting as bad every unit which would give a megger reading below 500 megohms, this test showed that out of about 22,400 units, 1621 or 7.3 per cent were found to have deteriorated.

The same line was gone over again in the autumn of 1914, about half a year after the first test, and showed an additional number of about 1020 or 4.7 per cent which had gone bad. This indicates clearly how rapidly this deterioration process is going on. All told, four years' operation produced 2640 bad units, or 11.7 per cent, an average of 2.9 per cent per year. Judging from the last test, it seems as though this deterioration goes on at a rapidly increasing rate year after year.

Table II shows the result from both tests combined, but gives the figures for strain and suspension towers and for the two circuits separately. It will be seen that the two circuits have practically the same number of bad units, but the strain towers on both circuits show a very much larger percentage (17.1 per cent) of damaged units than the suspension units (7.6 per cent), indicating that the horizontal strain units are very much more exposed to this trouble than the vertical suspension units.

A number of other tabulations has also been made up to see if there were any difference between insulators from the top, middle and bottom phases, or between the various units in a string. Only slight differences could be found, excepting between the different insulators in a suspension string. Taking

only the five first insulators in the string, which have been in service from the beginning of operation, we find that the top unit, *i. e.*, the one nearest to the crossarm, is the one most subject to damage. (See Table III).

After a number of these units were removed from the line, a series of tests was made in an attempt to determine the cause of this trouble. The tests were as follows:

First: 230 units with megger readings from 0.01 to 500 megohms were given a high-potential test (25 cycles). All of these units punctured before flash-over voltage, the puncture voltage varying widely, increasing in a general way, however,

TABLE II

NUMBER OF INSULATORS DETERIORATED ON PENNSYLVANIA WATER AND POWER COMPANY'S CIRCUITS NOS. 1 AND 2, 1911-1914.

Circuits	Strain insulators		Per cent damaged	Suspension insulators		
	Units tested	Units below 500 megohms		Units tested	Units below 500 megohms	Per cent damaged
No. 1	4,938	856	17.3	6,723	470	7.0
No. 2	4,942	832	16.8	5,900	485	8.2
Nos. 1 & 2	9,880	1,688	17.1	12,623	955	7.6

TABLE III.

SUSPENSION INSULATORS NOS. 1-5 DETERIORATED 1911-1914.

Unit No.	1	2	3	4	5
Circuits Nos. 1 and 2........	210	120	142	169	146

with an increased megger reading. Fig. 9 shows an attempt to express this relation in a curve. It will be seen that while a very low reading insulator will puncture at less than 20,000 volts, an insulator giving a megger reading above 300 megohms has a puncture voltage close to the flash-over point. This puncture takes place inside through the porcelain hidden between the pin and the cap. By continuing the current from the testing transformer until the puncture heated up, it could be felt, on the outside of the cap, that the breakdown generally took place on the side and very often close to the rim of the cap.

Second: While these tests were going on, a puncture of each

and every one of a string of five insulators occurred one day on the line, during actual operation. No lightning was reported, the weather was clear and no switching was done at the time of the disturbance. Fig. 10 shows this string. It can be seen that holes as large as a finger tip are burned through the porcelain and the cap, all on the side of the insulator, thus forming a short path between the pins and caps; no evidence of any simultaneous flash-over could be seen. It was a case of a clear puncture.

It was naturally thought that this was a case of deteriorated porcelain, which could have been caught in time to prevent

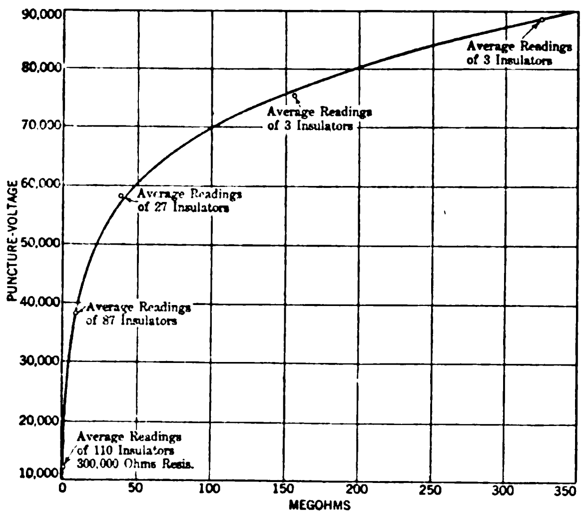


FIG. 9—RELATION BETWEEN MEGOHMS AND PUNCTURE VOLTAGE OF 230 INSULATORS TAKEN FROM THE BALTIMORE TRANSMISSION LINE IN THE EARLY PART OF 1914.

failure, if only megger readings had been taken of these insulators sometime beforehand. To prove this, five units removed from the line because of low megger readings were mounted in a string and high voltage was built up on them, not from a testing transformer, where the short-circuit current always is small, but from a 70,000-volt, 10,000-kw. transformer, with a 10,000-kw. generator behind it. The current was limited to about 250 amperes by a resistance.

The result of this test is shown in Fig. 11; when the voltage reached about 30,000 volts, the insulator punctured, burning porcelain and iron being, so to speak, shot out from the side of

first one, then of another insulator, leaving holes of just the same nature as found in the insulator string punctured on the line. (That the bottom insulator does not show any hole but only a hot spot is simply due to the fact that the current was taken off too early.)

Third: While the foregoing tests conclusively prove the serious nature of this insulator deterioration, they do not throw much light on the real nature and the cause of this trouble. The following tests were made with this object in view.

On 24 insulators discarded from the line because of low megger readings, the pin, cap and cement were dissolved in a diluted solution of nitric and hydrochloric acid so as to give an unobstructed view of the surface of the porcelain, normally hidden by the pin and cap. Of these insulators:

Seven showed clearly a tiny crack in the porcelain at the bottom of the head (see Fig. 12), a crack which was totally invisible as long as the cap covered it.

Three insulators showed similar cracks across the head.

Thirteen insulators did not show any cracks.

One insulator was destroyed during the test.

Trying with the megger on the cracked insulators, it could readily be shown that the low resistance was located right in the crack, and the most natural explanation of the reason for the low megger reading on these insulators would therefore seem to be moisture which has penetrated through the cement into this crack. To explain the crack itself, it has been suggested that this may have been caused by high internal stresses set up by uneven temperatures and expansion of the various parts in the insulator, which would be likely to occur, for instance, if the insulator becomes hot in the sun and is then suddenly cooled by rain. A. O. Austin has also suggested that crystalline growth in the cement may cause expansion of this, with consequent heavy stresses in the porcelain.

None of these explanations would seem to hold good for the insulators where no cracks could be found. On these insulators it was possible, however, by means of the megger, to trace areas of low resistance on the outside of the insulator head. It seems evident, therefore, that the acid used in dissolving the pin and cap had penetrated the unglazed body of porcelain between the pin and cap in spots, thus making it more or less conductive. But wherever acid can penetrate porcelain, it is natural to suspect that plain water can do the same. It is therefore believed

that the failure of these insulators is due to *porous material or lack of vitrification in the burning*, which gradually has allowed moisture to be absorbed by the porcelain in the same way as moisture has penetrated through the cracks in the cracked insulator.

Fourth: When it was first discovered that a large percentage of the low megger readings was due to cracks in the porcelain, it was naturally feared that these insulators had lost a great part of their mechanical strength. This proved, however, not to be the case. Twenty-five were picked out at random and tested in a pulling machine until mechanical failure. The ultimate strength of these insulators was found to vary between 6500 and 10,700 lb., with an average of 8100 lb., which is approximately the same as would be found on new, good insulators, when the cement had set thoroughly. Fig. 13 shows a typical break of one of these insulators, which does not differ in any way from the fracture shown by a perfectly good insulator.

Fifth: Hot and cold water test. When bids were requested for insulators for the new transmission line a series of tests was made on insulators submitted by different manufacturers, particularly with a view to finding the type of insulator that would seem to be least subject to depreciation. Working on the theory that the depreciation was at least partly due to high internal stresses, set up by temperature changes, the insulators were subjected to a hot and cold water treatment as follows:

Each insulator was dipped down in cold water (7 to 8.5 deg. cent.) and left there until thoroughly cooled (5 minutes); it was then taken up and within two or three seconds lowered into boiling water, head first. After remaining there for about five minutes, it was given a second temperature change by transferring it back into cold water, and so on. After each temperature change the insulator was tested with a megger and discarded if it gave a reading less than "infinity." If an insulator endured the treatment without any change in resistance it received in all 10 temperature changes. Table IV shows the result for six different types of insulators, designated A to F.

The insulators which had not been damaged by the hot and cold water test, so far as could be determined by the megger, were now subjected to high potential, with the results as shown in Table V.

TABLE IV

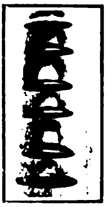
	Type	Weight per unit	Number of insulators		No. of single temperature changes withstood by insulators	Number of insulators that failed when transferred from	
			tested	failed		cold to hot	hot to cold
	A	8.5 lb.	19	6	141	3	2
	B	9 "	19	12	104	5	7
	C	10 "	19	12	88	4	8
	D	9.5 "	19	16	67	1	15
	E	11 "	6	0	60		
	F	11 "	6	2	40	2	

TABLE V

Type	Total No. insulators tested	No. units which withstood flash-over	Number of units and puncture voltage
A	13	6 (92 k.v)	7 (43 to 91 kv.)
B	7	3 (96 k.v)	4 (50 to 95 kv.)
C	7	1 (90 k.v)	6 (27 to 87 kv.)
D	3	0	3 (38 to 70 kv.)
E	6	6 (98 kv.)	
F	4	4 (85 kv.)	

These tabulations show that type E insulators withstood the tests the best, as none of them failed, while types C and D suffered the most, for, among 38 insulators treated, only one withstood the flash-over voltage afterwards.

The insulators which had already shown up poorly on the megger test were also given a high-potential test. They all punctured at voltages varying from 18,000 to 24,000 volts. The megger reading before test varied from 0.4 to 9 megohms. The cap and pin were also dissolved on two of the damaged insulators of types D and F. Both showed tiny cracks at the bottom of the head.

Sixth: Drying out of the insulators. Working on the other hand on the theory that, at least in part, this insulator trouble was due to absorption of moisture without accompanying cracks, the plan was tried of drying out some of the insulators removed from the line, under high vacuum and at temperatures varying from 50 to 90 deg. cent. A primitive air-tight tank which could contain 12 insulators at a time in a row was

installed, equipped with electrical heaters and connected to a vacuum pump, which would maintain a vacuum of about 27 in.

Altogether, three batches of a dozen insulators were dried out with this equipment. The drying out lasted from 10 to 20 days and megger readings were taken every few days. A graphic thermometer gave a continuous record of the temperature of the cap of one of the insulators.

The following observations were made:

A. After only a few hours' treatment, the insulation resistance decreases materially, probably because water is a better conductor when hot than when cold. After 24 hours' treatment a material increase is, however, always found, and this continues steadily until many of them reach the infinity mark, even when hot. All of them, without exception, will record infinity, when tested cold after two days' treatment.

After drying out, the insulators were given a high-potential test with 25 cycles.

B. *The result was that out of a total of* 37 *insulators tested,* 12 *withstood a heavy flash-over test for* ½ *min.* The rest of them punctured at voltages varying from 30,000 to 90,000 volts. As the megger readings on some of the insulators that withstood the flash-over were as low as 1 to 2 megohms before drying out, there cannot be any doubt but that they would have punctured at low voltages if they had not been treated.

C. The insulators which dried out the quickest punctured at the lowest voltages. These presumably were the cracked insulators. On the other hand, the insulators that withstood the high voltage generally increased very slowly in insulation. These perhaps were insulators which would not have shown cracks under the cap.

D. Four of the successfully dried out insulators have since that time, *i.e.*, for four months, been exposed to the weather, hanging in a vertical position. They still read infinity. It is believed that if means could be found to prevent moisture from re-entering such insulators, it would be perfectly safe to put them out on the line again.

It has often been suggested that the deterioration of insulators was due to electrical causes, such as switching, surges, arcing ground, high-frequency discharges, etc. As an indication that this is not the case, an insulator record from a 70,000-volt transmission line between Holtwood and Lancaster, 13 miles long, may be of interest. This line was built in the

summer of 1913. It consists of two identical circuits on the same tower line. While the two circuits were built at the same time, it has been customary to use only one of them, while the other one was kept as a spare. Both lines were gone over with a megger in the winter of 1914. At the end of the test one of the circuits had been under voltage 481 days, the other one only 91 days. Still they showed very nearly the same percentage of damaged units, *i.e.*, 8.9 per cent against 8 per cent.

It seems therefore clear that the influence of the voltage on the line in this respect is very small, if any.

On the whole, the insulator record given above, and the experiments made, all tend to show that the deterioration of the type of insulator in question is not due to electrical but rather to mechanical and ceramic causes.

Sleet. On the operating record, Table I, we find "sleet" next on the list.

It is now well understood that the most common cause of sleet trouble is the fact that when, with the arrival of milder weather, the sleet starts falling off the wires, it will often fall off one full span or several spans at one time but still remain on other spans. Such conditions result in unequal loading and therefore also extremely unequal sag for the different spans. If the wires of different phases, therefore, as on circuits Nos. 1 and 2, are in the same vertical plane, they are liable to come in touch with each other and produce short circuits. The few disturbances recorded as caused by sleet on the Baltimore transmission line have all been of this nature.

In building the new line to Baltimore it has been attempted to prevent or minimize this trouble by having the middle crossarm extend farther out (about 2 to 3 ft.) than the top and bottom one; a larger number of strain towers has also been used, so as to avoid having more than five suspension spans between two dead-end towers. It may be of interest to note that during a recent sleet storm where both the old circuits, Nos. 1 and 2, were short-circuited, due to sleet, the new one, No. 6, stood up without a single short circuit.

There is, however, another method of preventing sleet trouble, which the Pennsylvania Water and Power Company lately has adopted. The principle of this method is simply to keep the transmission lines so hot that no sleet whatever can be formed on them. The heat is produced by circulating electric current through the wires. Test and experience show that for

a 300,000-cir. mil aluminum cable, about 250 to 300 amperes is enough to keep the sleet from sticking to the cables; often even less current will do it. On the other hand, if ice already deposited on the wires is to be melted off, considerably more current is necessary. The present arrangement, when a sleet storm is reported and the load is at its lightest, is to leave only one circuit in service, which carries all the load (No. 6), while the two others are connected in series, short-circuited at one end and current is sent through them from two generators and two transformers.

If the load is heavier, all three circuits will be put in service, and if the current is not judged to be sufficient to prevent sleet, an arrangement is adopted by means of which wattless current is brought to circulate over the wires while they at the same time carry the load. This purpose is gained by dividing the generators at the power house into three groups, each of which through its respective transformers is connected with one transmission circuit. The three circuits are paralleled at the substation end. The field is now kept *open* on the generators for one of these groups, while the others are over-excited. Consequently the generators with the open field will draw their excitation from the a-c. side, but this current will first have to pass the transmission line. An increase of from 40 to 200 per cent in total current for the three lines, depending on the load conditions, can be secured this way. A limit is set by the current-carrying capacity of the station equipment.

Buzzards. Fourth on the list of disturbances we find the heading "Birds on Line." The birds troubling this line are turkey buzzards. These birds often choose the towers as a resting place and here they are liable to ground the line to the tower through their own bodies. There is especial danger if they sit on the crossarm right below the live wire, particularly in the case of the suspension towers of circuits Nos. 1 and 2, where two extra units have been added; the clearance here is so small (only 24 in.) that even a small buzzard, the moment it starts to fly away, easily will reach the line overhead with the tip of its wing, while it still touches the tower with its feet. A buzzard grounded in this way is always killed and will generally drop down to the foot of the tower where it afterwards can be found. Fig. 14 shows a good-sized sample. (Toe to beak 22½ in., tip to tip of wings 65 in., tip of wing to toe 34 in.). Often they will fall down without even causing a voltage dis-

turbance, but frequently they will give rise to an arcing ground, which may even develop into a two-wire short circuit.

On the new line (circuits Nos. 5 and 6) the minimum clearance from wire to ground is 47 in., so it is hoped that this line will prove "buzzard-proof."

Wires Blowing Together. The one voltage disturbance recorded as being due to this cause, represents a case where the ground wire swung into one of the power cables at a place, on a special tower, where the clearance distance was abnormally small. It is therefore of no special interest.

Protective Devices

Let us review the transmission line troubles:

They were caused by:

1. Lightning.
2. Defective insulators.
3. Sleet.
4. Buzzards.
5. Wires blowing together.

It has been described how the company has tried to maintain and improve its lines and operating methods so as to avoid, as far as possible, trouble from the above causes. In order to maintain continuous operation, also, when grounds or short circuits, due to any of the above causes, occur on the line, several different protective devices have been adopted, which are briefly described below:

1. *Interlocking Line Relay.* Trouble from defective insulators, sleet, buzzards, and the wind swinging the wires together, generally, if they give any trouble whatsoever, result in grounds or short circuits that persist on the system until the voltage is taken off the faulty line; sometimes it may even result in a permanent fault, that does not permit restoration of voltage until repairs are made. The natural method to safe-guard operation against such troubles is therefore to cut the damaged line out, and the earlier the better. This means, as a general scheme, automatic operation of switches.

The system in use is illustrated in Fig. 16. It consists simply of overload relays at the power house connected in series with the line current transformers and also one relay in the ground connection for the neutral of each transformer bank. At the substation, reverse-current relays take the place of the overload relays at the power house. All these relays are them-

selves made as instantaneous in their action as possible, but they do not act directly on the trip circuit of their respective oil switches, but are used in connection with definite time limit relays set for various time-elements ($\frac{3}{4}$ to 3 seconds) so that a momentary short circuit will not produce action. To prevent all three lines from going out by relay action, in case there should be a short circuit on all the lines at the same time, the trip circuits are interlocked.

This system has, with various minor changes, been used since the starting of the plant. It has not always been entirely successful. Difficulties were especially encountered in giving the various relays a suitable current and time setting, and due to the complication in wiring introduced, since low-tension automatic switching was adopted. Since June, 1914, when various changes were made, especially on the reverse-current relays, so that they would be more sensitive, the record shows seven entirely successful actions, out of a total of nine times when the conditions were such that they could act correctly.

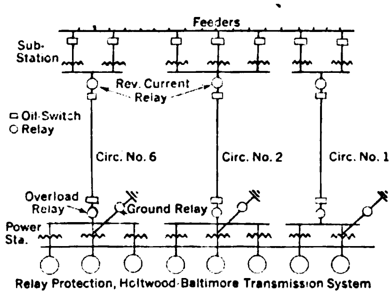


FIG. 16—SIMPLIFIED DIAGRAM OF TRANSMISSION SYSTEM, SHOWING LOCATION OF LINE RELAYS

It may be asked why the same interlocking relay arrangement is not sufficient as lightning protection. The reason is the simple fact that lightning flash-overs very often will occur on both circuits Nos. 1 and 2 at the same time. (It still remains to be seen whether they will occur on all three circuits at the same time.) When both circuits are in trouble at the same time, the clearing of both means, of course, a total interruption.

Even during the first year's lightning season it was noticed that though the lightning short circuits were so severe that it was necessary to clear the circuits, the insulators and cables were never so badly damaged that it was impossible to come right back with the voltage, right after the interruption. This indicated clearly that if only some means could be found to extinguish the power arcs, an interruption might be avoided.

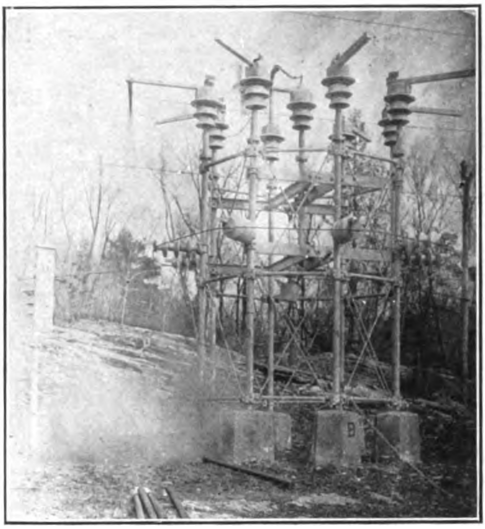
The first scheme tried with this end in view was based on the idea of clearing one line completely, by means of the high-tension oil switches at both ends, while the other one, even

if in trouble, was supposed to maintain some kind of synchronism with the customers' load; then immediately, *i.e.*, as fast as the oil switches could do it, the first circuit would be put right back again and the second line cleared, etc. The system was actuated by overload relays at Holtwood and their action was transmitted by means of overhead wires to other relays at the substation, so as to get synchronous action of the oil switches. This system proved a failure mainly because it was found that certain atmospheric conditions of no danger to the high-tension transmission lines, would produce discharges through the overload relay wires and thus unnecessarily actuate the relays at the substation and trip the oil switches. The system was therefore soon discarded.

The next system adopted, which is still in use, was the arc extinguisher arrangement invented and designed by Mr. L. C. Nicholson, Buffalo, N. Y. The principle of this arrangement is to shunt any arc that arises on the line with a fuse wire, so that the current, as long as the fuse lasts, will prefer this path to the arc. The fuse is calibrated to blow in from 5 to 10 cycles (25-cycle system) and this short time, experience has proved, is enough to extinguish the arc on the line; therefore as soon as the fuse blows, the line will be clear again. The fuse wires are connected across the proper wires automatically by means of specially designed magnetic relays and switches. The whole arrangement is placed right outside the power house. The design of the equipment is such that seldom more than one cycle will pass from the time the lightning arc is established until the switch is closed. It is in this speed that the apparatus has its greatest advantage, since it allows the arc on the line so very little time to spread and do damage.

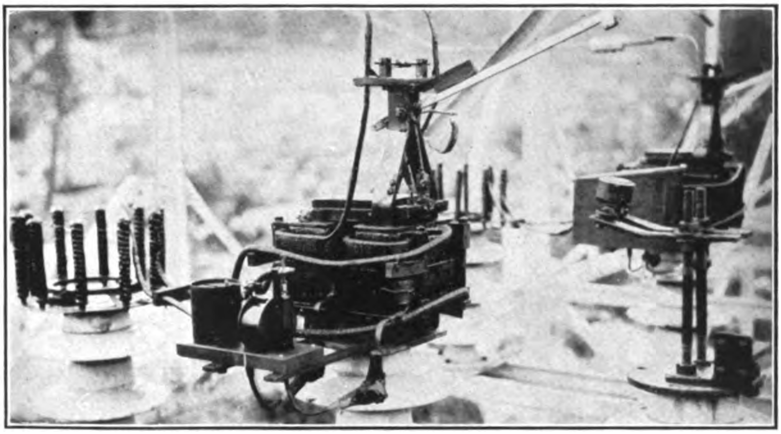
An important point for successful operation is to have the fuses timed correctly. If this time is too short the arc may be re-established, and if too long, it is very difficult for the synchronous load to remain in synchronism. The size of the fuse to use was originally determined by test. As a check against values found this way, cycle recorders are also installed between the fuse banks, so that an actual record of the time it takes a fuse to blow, during a lightning storm, always can be found afterwards.

Figs. 20A and 20B are two oscillograms which illustrate the action the short-circuiting of the lines with such fuses has on the system. One oscillograph was mounted at the power house



[BANG]

FIG. 18—NICHOLSON ROTARY FUSE BANK. THE PHOTOGRAPH WAS TAKEN AT THE INSTANT THE FUSE BLEW



[BANG]

FIG. 18—NICHOLSON MAGNETIC SWITCH AND RELAY

and one at the substation. On both oscillograms the two outer curves represent the low-tension bus voltage, while the middle wave represents the high-tension line current. The short circuit was a three-phase one made with No. 16 B. and S copper wire. Two generators of 10,000 kw. capacity were feeding a synchronous load of seven 1000-kw. synchronous con-

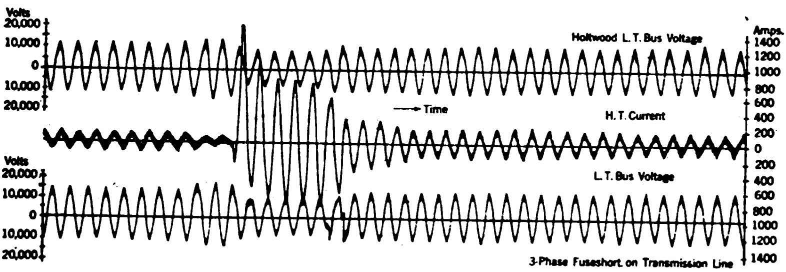


Fig. 20a—Three-Phase Fuse Short Circuit on Transmission Line
The middle wave represents the high-tension current, the others the low-tension bus voltage at the power house.

verters over one line. It will be seen that the fuse blew in $5\frac{1}{2}$ cycles.

As the relays work on the principle of overload, the fuses are now only put in service when a lightning storm is reported. Otherwise it can not be prevented that fuses unnecessarily will blow and thus introduce undesirable complications when

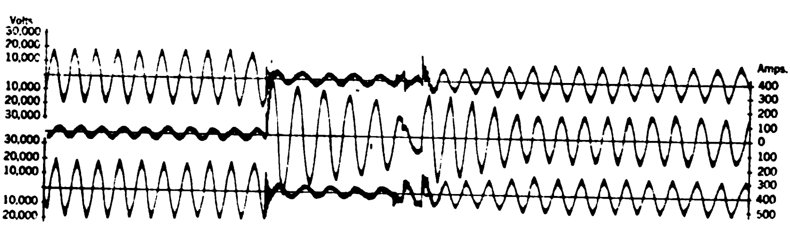


Fig. 20b—Same as Fig. 20a
The middle wave represents the high-tension current at the substation, the two outer ones the low-tension bus voltage at the substation.

short circuits occur on the low-tension system, and on other occasions when their action cannot possibly be of any benefit.

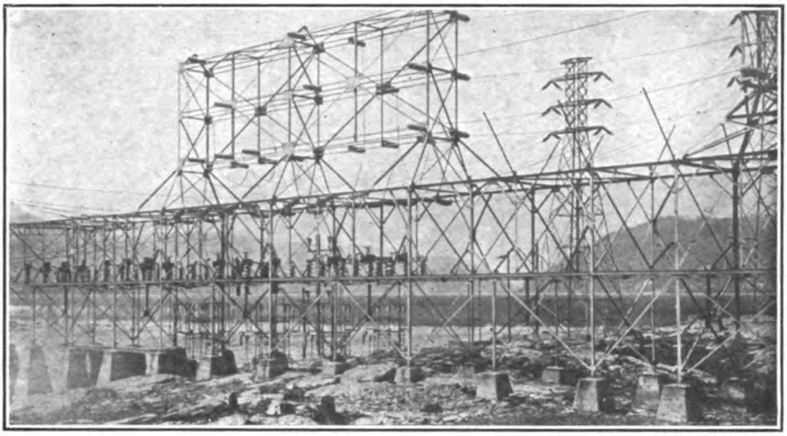
This device is especially satisfactory on the Baltimore line when only a ground or two-wire short circuit occurs. In such cases it saves all or practically all the synchronous load. On three-phase short circuits the action is more severe, but generally about 50 per cent of the load can be saved, especially if the

synchronous converters of the connected load are separately excited or by other means prevented from reversing polarity. By keeping the voltage on the line all the time it makes it also possible to restore lost load more quickly than otherwise would be the case. In 1913 and 1914 it cleared the line successfully a total number of 25 times out of 40 times the lightning hit the line. Wherever it has failed it has generally been possible to trace the cause to using a fuse of the wrong size.

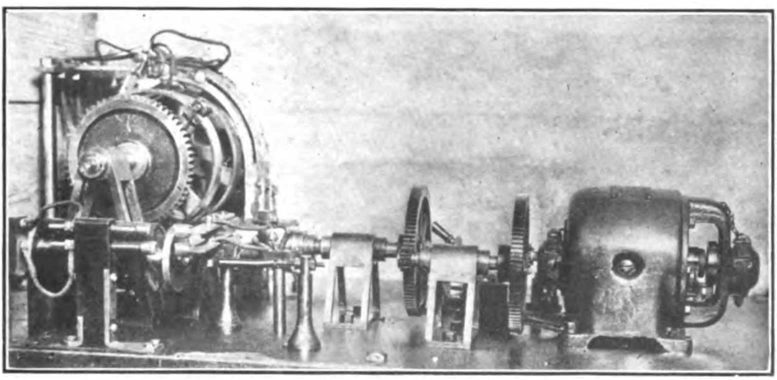
Another lightning protective device in use which also has as its purpose, not to prevent lightning flash-overs, but to minimize their consequences by extinguishing the arcs, is the so-called field destroying and restoring device invented by Mr. F. E. Ricketts, of Baltimore.

The principle of this device is simply that whenever a short circuit occurs on the line, the field of all the generators will for a moment be destroyed, so as to allow the arc on the line to be extinguished on account of lack of voltage, and then immediately after be built up again so as to force the synchronous load into step again before the synchronous converters, frequency changers, etc., have come to a stop. The necessary switching for operating this device is naturally done automatically.

The actuating relays are in this case either an overload relay (of the ordinary plunger type) in the generator circuit, or the above-mentioned relays in the neutrals of each transformer group. Both of these relays act as instantaneously as relays of their type will permit, but in order to give the Nicholson arc extinguisher and the interlocking relay arrangement the first chance to clear the trouble, they are used in connection with a definite time element, at present set for four seconds. When these four seconds are up, a clutch for a small motor, which is running continually, will be thrown in contact and start a drum rotating. On this drum contacts are arranged so that as soon as it starts all the ordinary field circuit breakers (one for each generator,) will be opened simultaneously, at the same time short-circuiting the field windings across their respective discharge resistances, thus allowing the field gradually to die out and the line voltage to be reduced correspondingly. Meanwhile the drum continues to revolve and will, after a predetermined time (originally 5 sec., now $1\frac{1}{2}$ sec.), close other contacts which have the effect of slamming all the circuit breakers in again. Immediately the fields and line voltage start to



[BANG]
FIG. 19—GENERAL ARRANGEMENT OF NICHOLSON ARC EXTINGUISHER SHOWING STRUCTURE FOR LOCATION OF RELAYS AND IN THE BACKGROUND A SET OF ROTARY FUSE BANKS



[BANG]
FIG. 21—RELAY MOTOR AND REVOLVING DRUM FOR RICKETTS FIELD—DESTROYING AND RESTORING DEVICE

build up again. After some surging between the generators themselves individually and the generator and synchronous load, the voltage will again be normal, generally after about one minute. The drum continues to rotate until it has made one complete revolution, after which time it is disengaged from the motor and the whole equipment ready for another operation.

The record for this device shows for 1913 and 1914 a total number of 12 successful lightning operations and 4 failures.

Comparing this device with the Nicholson arc extinguisher, it must be said that the fuse arrangement has been given preference and first chance for acting, mainly on account of its quickness of action, which saves the line from too severe damage, and also on account of the excellent results it has produced in case of the lesser lightning disturbances like grounds and two-wire short circuits.

The field-destroying device treats all lightning disturbances as equally severe and produces the same disturbance on practically all of them, but seems, on the other hand, to have the great advantage of extinguishing the arcs with more certainty.

Difficulties with this device can mainly be traced back to the waterwheel governors. It is especially difficult when the synchronizing power between the generators themselves for a moment is lost with the field, to prevent a generator whose prime mover is on hand control (*i.e.*, has a steady gate opening), from speeding up beyond the others. Much improvement in this respect has, however, been gained by decreasing the time the field was left off from 5 seconds to $1\frac{1}{2}$ seconds.

Conclusion

It has been shown that while lightning still gives rise to a number of disturbances, these have been very materially reduced both in number and in severity, year for year, by the use of special protective devices. As to sleet, special operating methods have been adopted during such storms, which it is believed will prevent trouble from this cause. The approaching danger from deterioration of the insulators has been discovered at an early stage, and rigid and repeated elimination tests of bad insulators, with megger, have been adopted as part of the routine maintenance, so that it is felt that *operation* will have but little to fear from this source.

A. I. E. E. Panama-Pacific Convention, September 16-18, 1915.
International Engineering Congress, September 20-25, 1915.

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CONTENTS OF SECTION I.

Section II.—Papers, Discussions and Reports

FOR CONTENTS OF SECTION II SEE TITLE PAGE OF SECTION II

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A.I.E.E. STANDARDIZATION RULES

EDITION OF JULY 1, 1915

The new edition of the Standardization Rules, as recommended by the Standards Committee and adopted by the Board of Directors, to take Effect July 1, 1915, is published in this issue of the PROCEEDINGS, and pamphlet copies are also available at a cost of 25 cents per copy. This edition of the Rules is substantially the completion and clarification of the 1914 edition, although some important additions have been made.

By action of the Board of Directors, copies of the new edition of the Rules have been supplied free of charge to all persons who had obtained copies of the 1914 edition.

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OF
Electrical Engineers.

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THE EDITING COMMITTEE

GEORGE R. METCALFE, Editor

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Panama-Pacific Convention, and International Engineering Congress

As announced in previous issues of the PROCEEDINGS, the Panama-Pacific Convention of the Institute will be held in San Francisco, September 16 to 18, 1915.

Conventions will also be held in San Francisco upon the same dates by the American Society of Civil Engineers, the American Society of Mechanical Engineers and the American Institute of Mining Engineers.

The International Engineering Congress, which has been organized by the four societies named above and the Society of Naval Architects and Marine Engineers, will be held during the week immediately following; namely, September 20-25, 1915.

The local committees representing the various organizations concerned are cooperating in formulating the plans for these several meetings, thus insuring the advantages of a harmonious and comprehensive program of technical sessions, inspection trips, and other interesting features, to all who attend this general gathering of the engineering profession in San Francisco.

Transportation

The transportation arrangements from the East to these various conventions and the Congress have been made by a joint committee on reception and transportation, and have been announced in detail in a special circular issued to the membership of all the participating societies in March, 1915. Briefly, these arrangements include a special train leaving New York City at 7:45 p.m., Thursday, September 9, and arriving in San Francisco at 9 p.m. on Wednesday, September 15, with stop-overs at Niagara Falls, Colorado Springs, and the Grand Canyon. A special train will also leave New Orleans on Sunday, September 12 at 11 a.m., via the Southern Pacific Railway, arriving in San Francisco on Wednesday, September 15, at 1 p.m. Members may join either special train en route. There will be no return special train service, but members will have their choice of several return routes. Rates for the special trips: The fare from New York to San Francisco, and return by any other route except via Portland, Ore., (good for three months), is $98.80. The return trip via Portland is $17.50 extra. The side trip from Williams to Grand Canyon is $7.50. Pullman rates from New York to San Francisco are: one way, lower berth, $22.00, upper berth, $17.60, compartment, $62.00 (one and one-half railroad fares required for use of one person), drawing room, $77.00 (two railroad fares required).

Reservations for this train are being made by G. S. Harner, Passenger Agent, New York Central Lines, 1216 Broadway, New York City, and applications for reservations should be made promptly to him. Mr. Harner will arrange for the transportation of those desiring to travel on this train, and for their return over any other line, or at any time specified.

The fare from New Orleans to San Francisco and return is as follows:

Round trip fare, New Orleans to San Francisco and return, good for three months, $57.50, going and returning over the same route, or going via the Southern Pacific and returning via Santa Fe; round trip fare, New Orleans to San Francisco, returning to Chicago, $62.50. Pullman rates, New Orleans to San Francisco, one way, lower berth, $11.50, upper berth, $9.20, drawing room, $41.00 (two railroad fares required), compartment, $32.50 (one and one-half railroad fares required for use by one person).

Reservations for this trip may be made by addressing J. H. R. Parsons, General Passenger Agent, Southern Pacific Company, New Orleans, La. In asking for reservations the statement should be made that the request is in connection with the engineering party. Reservations will be made in one car until that is filled, and so on; and should there be a sufficient number, the party can have a special train.

Hotel Accommodations

The headquarters of the Institute will be at the St. Francis Hotel, which is only a block away from the Native Sons of the Golden West Building, in which the Institute convention sessions will be held. Information regarding rates at the St. Francis and many other San Francisco hotels was published in the special circular referred to above. Members expecting to attend the convention are advised to make reservations for hotel accommodations promptly. If desired the Panama-Pacific Convention Committee will be glad to make reservations for accommodations for Institute members, in which case application should be made by telegram, letter or otherwise, as promptly as possible, to Mr. W. W. Briggs, Chairman, 14 Sansome Street, San Francisco, Cal., giving hotel preferred, specific information regarding the date of arrival, character of accommodations and approximate rates desired. In order to avoid duplication of work, members should also advise Mr. Briggs whether or not th[illegible] taken up the question of hot[illegible] tions with any other engineeri[illegible] or directly with any other ho[illegible]

The Panama-Pacific Conven[illegible] mittee of the Institute, which [illegible] ing its time to planning for [illegible] vention and providing for th[illegible] and entertainment of visiting [illegible] is composed as follows:

Messrs. W. W. Briggs, Chair[illegible] H. Babcock, A. G. Jones, H. A. [illegible] J. T. Whittlesey, and C. J. Wils[illegible] San Francisco; Prof. C. L. C[illegible] versity of California; Prof. [illegible] Ryan, Leland Stanford, Jr., U[illegible] Mr. L. T. Robinson, Chairm[illegible] tute Meetings and Papers Co[illegible] Messrs. H. H. Barnes, Jr., an[illegible] F. Sever, of New York.

Technical Program of Panama-Pacific Convention

The following is a progran[illegible] technical sessions of the In[illegible] Panama-Pacific Convention.

Reprints of all convention [illegible] will be available without ch[illegible] registration headquarters.

THURSDAY, SEPTEMBER [illegible]

10:00 A.M.

Opening Ceremonies.

10:30 A.M.

The convention will separat[illegible] two parallel sessions, as follow[illegible]

1. *Physical Limitations in D-C. Commutating Machinery*, by [illegible] Lamme.
2. *Automatically Controlled [illegible]tions*, by E. W. Allen and [illegible] Taylor.

Marine and Lighting Session.

3. *Standard Marine Electrical In[illegible]lations*, by H. A. Hornor
4. *Recent Improvements in [illegible] Lighting of Steam Railroad [illegible]*, by R. C. Lanphier.

2:30 P.M.

Three parallel sessions will be held as follows:

Electrophysics Session.

5. *The Effects of Transient Voltages on Dielectrics*, by F. W. Peek, Jr.
6. *Arc Phenomena*, by A. G. Collis.
7. *Experimental Researches on Skin Effect in Conductors*, by A. E. Kennelly, F. A. Laws, and T. H. Pierce.

Valuation of Public Utilities Session.

Symposium on Inventories and Appraisals of Properties.

8. *Part I*, by C. L. Cory.
9. *Part II*, by W. G. Vincent.
10. *Part III*, by W. J. Norton.

These papers will be supplemented at the session by contributions from other members of the Committee on Inventories and Appraisals of Properties.

Joint Session with the Institute of Radio Engineers.

11. **Sustained High Frequency High Voltage Discharges*, by Harris J. Ryan and Roland G. Marx.

*The Institute of Radio Engineers' paper. For copies of this paper apply to R. B. Woolverton, Radio Inspector, Customs House, San Francisco.

FRIDAY, SEPTEMBER 17

10:00 A.M.

Two parallel sessions will be held, as follows:

Telephony and Telegraphy Session.

12. *Submarine Cable Rapid Telegraphy: Ocean and Intercontinental Telephony*, by Bela Gati.
13. *Automatic Switchboard Telephone System of Los Angeles, Cal.*, by W. Lee Campbell.
14. *Continuation of discussion on Inductive Interference.* Introduced by Joint Committee on Inductive Interference.

Mine Work Session.

15. *Diesel Engines for Generator Drive*, by Charles Legrand.
16. *A Large Electric Hoist*, by Wilfred Sykes.
17. *The Modern Electric Mine Locomotive*, by Graham Bright.

2:30 P.M.

Three parallel sessions will be held, as follows:

Joint Session with the American Electrochemical Society.

18. *Overhead Electrolysis and Porcelain Strain Insulators*, by S. L. Foster.
19. **Corrosion of Copper Wireless Antennae*, by L. W. Webb.
20. **Electrochemical Possibilities in California and on the Pacific Coast*, by J. W. Beckman.

*American Electrochemical Society's papers. For copies of these papers apply to Dr. Joseph W. Richards, Secretary, South Bethlehem, Pa.

Transmission Session.

21. *Delta-Cross Connection of Transformers*, by G. P. Roux.
22. *Harmonics in Transformer Magnetizing Currents*, by J. F. Peters.
23. *Phenomena Accompanying Transmission with some Types of Star Transformer Connections*, by L. N. Robinson.
24. *Abnormal Voltages in Transformers*, by J. Murray Weed.
25. *Calculation of Short-Circuit Phenomena of Alternators*, by N. S. Diamant.

Joint Session with the Institute of Radio Engineers.

26. **Radio Development in the United States*, by Robert H. Marriott.

*The Institute of Radio Engineers' paper. For copies of this paper apply to R. B. Woolverton, Radio Inspector, Customs House, San Francisco.

Meetings of Other Societies

The headquarters of the three other national engineering societies which are to hold conventions in San Francisco on September 15-18 will be as follows:

Society	Hotel Headquarters	Meeting Place
A. S. C. E.	St. Francis	Hotel
A. I. M. E.	Bellevue	Hotel
A. S. M. E.	Clift	Native Sons of the Golden West Building.

The meeting of the American Society of Civil Engineers is the Forty-Seventh Annual Convention of the Society. The program includes a welcoming address by President Charles D. Marx; a Panama Canal session; a reception, dinner and dance in the Old Faithful Inn on the grounds of the Panama-Pacific International Exposition, and excursions to Del Monte, Santa Cruz and San Jose. The Society, through its Secretary, Charles Warren Hunt, has extended a cordial invitation to the membership of the Institute to participate in these events.

International Engineering Congress

Information regarding the plans for the International Engineering Congress, which have been made by a Committee of Management consisting of representatives of the societies interested, has been given in previous announcements in the PROCEEDINGS, and in various circulars issued during the past year. The technical program will include papers under the following classifications: Index and Digest; The Panama Canal; Waterways, Irrigation; Railways; Municipal Engineering; Materials of Engineering Construction; Mechanical Engineering; Electrical Engineering, Mining Engineering, Metallurgy; Naval Architecture and Marine Engineering; Miscellaneous, including Military Engineering, Aeronautical Engineering and Heating and Ventilation.

Over 3,000 members have already been enrolled.

Members of the Institute who have not yet enrolled in the Congress, and who desire to do so, should send their remittance of $5.00 to W. A. Cattell, Secretary, Foxcroft Building, San Francisco, Cal. This nominal fee entitles subscribers to a certificate of membership, to participate in the deliberations of the Congress, to an index volume of the Proceedings, and to one of the volumes covering the technical subjects indicated above. Additional volumes may be purchased at a nominal price. The Congress will be opened at 10 a.m., Monday, September 20. Sessions will be held in the New Civic Auditorium Building. Programs of the Congress may be obtained upon application to W. A. Cattell.

Technical Excursions

As announced in the July PROCEEDINGS, the Committee of Management of the Congress has published a circular containing an outline of the various excursions to points of engineering interest which have been arranged in conference with the local committees of the other societies concerned, and which will be open to all members and guests attending the Congress or any of the conventions referred to above. Copies of the circular may be obtained upon application to the headquarters of the Committee on Management, Foxcroft Building, San Francisco, or to the Secretary of the Institute.

These excursions include visits to the San Francisco High-Pressure Fire-System; the Potrero Gas Works, and Electric Station "A", Pacific Gas and Electric Company; Spring Valley Water Works properties on east side of San Francisco Bay; Spring Valley Water Works Storage Reservoirs and Pumping Stations, on the San Francisco Peninsula; the Delta Lands of the Sacramento and San Joaquin Rivers; Great Western Power Company's Hydroelectric Development on the Feather River; Gold Dredging at Oroville; Gold Mines at Grass Valley; Spaulding Drum Development of the Pacific Gas and Electric Company; and the Oil Fields at Coalinga.

Association of Iron and Steel Electrical Engineers' Annual Convention

The annual convention of the Association of Iron and Steel Electrical Engineers will be held at the Hotel Statler, Detroit, September 8-11, 1915. There will be joint sessions with the American Institute of Electrical Engineers on Thursday, September 9, which all

members of the Institute are invited to attend. For the joint sessions there will be three papers presented by the Iron and Steel Electrical Engineers, and one paper and one lecture by the American Institute of Electrical Engineers, the titles of which are as follows:

Automatic Aids to Power Plant Operation, by C. P. Steinmetz.

Description of Modern Developments, by P. M. Lincoln.

Latest Electrical Developments, by K. A. Pauly.

Progress in the Iron and Steel Industry and the Electric Furnace, by Karl Georg Frank.

Lecture on Mechanical Analogies in Electricity and Magnetism, by W. S. Franklin.

Copies of the program may be obtained by interested members upon application to Mr. W. T. Snyder, Secretary of the Association of Iron and Steel Electrical Engineers, McKeesport, Pa.

Institute Meeting in Philadelphia, Pa., October 11, 1915

An Institute meeting will be held in Philadelphia, Pa., on Monday, October 11, 1915, under the auspices of the Philadelphia Section. This meeting was authorized by the Board of Directors of the Institute on April 9, 1915. A complete program will appear in a later issue of the PROCEEDINGS.

Institute Meeting in St. Louis, Mo., October 19 and 20, 1915

A two-day Institute meeting will be held in St. Louis, Mo., under the auspices of the St. Louis Section, on Tuesday and Wednesday, October 19 and 20, 1915. The meeting was authorized by the Board of Directors of the Institute on April 9, 1915, upon request of the St. Louis Section, and it will be the occasion of the 100th meeting of that Section. The local officers are arranging an attractive program of interesting papers and other features, which will be published later.

Convention of Illuminating Engineering Society, Washington, September 20-23, 1915

The Illuminating Engineering Society will hold its ninth annual convention at the New Willard Hotel, Washington, D.C., September 20-23, 1915. The papers, which promise to be of an unusually high standard, will be distributed over ten sessions.

The preliminary draft of the program shows 36 titles of papers, in addition to committee reports, etc. One of the sessions will be devoted especially to the subject of street lighting; commercial, general and laboratory papers will each be given three sessions. Inspection trips, a reception, and a banquet are among the entertainment features.

Information regarding the convention may be had upon application to the general office of the Society, 29 West 39th Street, New York.

A. I. E. E. Mortgage Paid

At the May meeting of the Board of Directors the Finance Committee reported that it had considered the advisability of paying off the remainder of the Institute's share of the indebtedness upon the land occupied by the Engineering Societies Building, amounting to $54,000. The conclusion reached by the committee was that the best interests of the Institute would be served by the payment of the mortgage at this time, and it recommended that this action be taken. The Board approved the recommendation, and authorized the Finance Committee to sell, through the Treasurer and the Secretary, such securities owned by the Institute as would be necessary to make up the required amount.

At the meeting of the Board at the Deer Park Convention on July 1, the Finance Committee reported that in accordance with the action of the Board taken at the May meeting the necessary securities to make up the sum required for the payment of the mortgage had

been sold, and the payment of the $54,000 had been made on June 25, 1915, thus completing the payment of $180,000, representing one-third of the $540,000 which was the cost of the land upon which the Engineering Societies Building stands.

The membership is to be congratulated upon the fact that the Institute was able to discharge its mortgage indebtedness without the necessity of curtailing any of its present activities.

The other two founder societies, namely, the American Society of Mechanical Engineers, and the American Institute of Mining Engineers, have also completed their payments of $180,000 each, and therefore the entire mortgage upon the property of the United Engineering Society, which is composed of representatives of the three founder societies, the A. S. M. E., the A. I. M. E., and the A. I. E. E., has now been satisfied.

Amendment to By-Law Providing for Student Enrolment

Acting upon the recommendation of the Board of Examiners and the Sections Committee, the Board of Directors at its meeting held on July 1, 1915, at the Deer Park convention, amended Section 61 of the Institute by-laws providing for the enrolment of students. The by-law was amended so that the privilege of student enrolment may be extended to the students of all educational institutions giving courses of instruction in electrical engineering subjects. The former by-law provided that "any person pursuing a regular course of study in electrical subjects and registered as a student in any university or technical school of recognized standing," might be enrolled, and under a ruling by the Board of Directors a few years ago, the term "technical school of recognized standing" was interpreted to apply to schools of college grade giving a course of not less than three years in electrical engineering and granting degrees. Therefore, electrical engineering students in schools not of college grade were not able to avail themselves of the privileges of enrolment in the Institute, which include the regular receipt of the Institute PROCEEDINGS. The question was discussed at the meeting of the Board of Examiners held on May 17, and a resolution was passed recommending to the Board of Directors that the restriction be removed so far as it applied to student enrolment.

The text of the by-law as amended is as follows:

Sec. 61. Any person registered as a student in any educational institution, pursuing a regular course of study in electrical subjects. and attending classes therein, may be enrolled as a "Student of the American Institute of Electrical Engineers," as hereinafter provided.

Deer Park Convention

The thirty-second annual convention of the Institute was held in accordance with the program previously announced, at the Deer Park Hotel, Deer Park, Md., June 29-July 2, 1915. The total number of members and guests in attendance was 202, including 43 ladies. Although conditions this year were not conducive to a large attendance, nevertheless those who did attend were amply repaid, as the convention was in every way satisfactory, both from an engineering and social viewpoint. The papers and discussions were of the usual high grade and the enjoyment of all in attendance was greatly enhanced by the excellent arrangements made by the Convention Committee for the entertainment of members and guests.

Tuesday Morning

The convention was called to order at 10:50 a.m. Tuesday by President Paul M. Lincoln, who delivered his Presidential Address, on "The Trend of Electrical Development." (This is printed in Section II of this issue.) After announcements by Mr. Farley Osgood, chairman of the Games Committee, the technical program for the morning was taken up.

Dr. John B. Whitehead presented his paper, *The Electric Strength of Air—VI.* After discussion on this paper, Mr. Percy H. Thomas, in the absence of the author, presented Mr. John F. H. Douglas's paper, *The Reluctance of Some Irregular Magnetic Fields.* Dr. Frederick Bedell followed with the presentation of the series of three papers, under the general title *Irregular Wave Forms,* prepared by Frederick Bedell, R. Bown, H. A. Pidgeon, C. L. Swisher, and F. M. Mizushi. The time allotted for the discussion on this series was taken up with the reading of a 3500-word contribution telegraphed from San Francisco to Pittsburgh by the California Joint Committee on Inductive Interference, and relayed by telephone that morning from Pittsburgh to Deer Park.

Tuesday Afternoon

The program for Tuesday afternoon began with the presentation of five papers on *Foundation for Transmission Line Towers, and Tower Erection,* prepared by Messrs. J. A. Walls, J. B. Leeper, W. E. Mitchell, P. M. Downing, and F. C. Connery. Mr. Leeper presented his paper, and, as none of the other authors was present, Mr. Percy H. Thomas, chairman of the Transmission Committee, abstracted the remaining four papers. Mr. Thomas then abstracted a paper by Mr. A. Bang, entitled *Four Years' Operating Experience on a High-Tension Transmission Line* (published in July, 1915, PROCEEDINGS), which was first presented at the meeting of the Baltimore Section on February 26, 1915, and scheduled for discussion at the Deer Park Convention.

After the discussion on the foregoing papers, Mr. D. B. Rushmore, chairman of the Industrial Power Committee, presented his topical discussion on *Fields of Motor Application,* and introduced the speakers who had prepared short papers on particular phases of motor application. Mr. Rushmore also presented Mr. H. E. Stafford's paper on *Electricity in Grain Elevators.* The subject was then opened for a general discussion from the floor.

Tuesday Evening

The usual reception and dance was held at the hotel on Tuesday evening, June 29. Those who received were: President Paul M. Lincoln and Mrs. Lincoln, of Pittsburgh, President-elect John J. Carty, of New York, Mrs. Farley Osgood, Newark, N. J., Honorary Vice-President Harris J. Ryan, of Stanford University, Cal., Mrs. Comfort A. Adams, of Cambridge, Mass., Past-President Dugald C. Jackson, of Boston, Mrs. J. Franklin Stevens, of Philadelphia, and Secretary F. L. Hutchinson, of New York.

About 150 were present on this occasion and an excellent orchestra provided music for dancing, which was continued until after midnight.

Wednesday Morning

On Wednesday morning President Lincoln called the meeting to order at 9:30 o'clock, ahead of the scheduled time, to allow for the completion of the discussion on *Irregular Wave Forms,* continued from the Tuesday morning session. At the close of that discussion, the president called for the presentation of the two papers, *Classification of Alternating-Current Motors,* by Val. A. Fynn, and *The Classification of Electromagnetic Machinery,* by Frederick Creedy. Professor Comfort A. Adams, secretary of the Standards Committee, made an introductory statement, describing the difficulties the committee had met with in trying to devise a system of nomenclature for alternating-current motors, and said that for that reason the two papers of the session had been prepared at the request of the Standards Committee in order to bring the subject up for general discussion. Mr. Fynn then presented his paper, and Professor Adams presented the paper by Mr. Creedy, and the two were discussed together.

Wednesday Evening

The Wednesday evening session was called to order at 8:30 o'clock, and President Lincoln introduced President-elect J. J. Carty. Mr. Carty made a brief address, expressing his sense of the honor conferred upon him by the membership of the Institute. In referring to the successful year the Institute had enjoyed under the guidance of President Lincoln, Mr. Carty mentioned three things for which the year was notable—the growth in solidarity and the disappearance of sectional feeling in the Institute, due largely to Mr. Lincoln's long-continued interest in the Sections and his efforts to tie them together as parts of one great national institution, the paying off of the Institute's share of the mortgage on the Engineering Societies Building in New York, and the movement for the welfare of the engineer as a man, signalized at the meeting called to discuss "The Status of the Engineer."

The president then introduced Professor Harris J. Ryan, Honorary Vice-President of the Institute on the Pacific Coast. Professor Ryan brought the greetings of the membership on the coast to the annual convention, and extended an invitation to all to come to the engineering congresses to be held in San Francisco in September in connection with the Panama-Pacific International Exposition.

Mr. Farley Osgood then made the presentation of the Past-President's badge to President Lincoln, expressing the appreciation of the Board of Directors and the Institute for his services during the year, and the pleasure the Directors had had in working with him.

In his response, President Lincoln spoke of his gratitude for the support that had been given him by the members of the Board of Directors and the standing and special committees. He then called upon President A. S. McAllister of the Illuminating Engineering Society to preside at the technical session, a joint meeting of the Society and the Institute.

President McAllister called upon Mr. Preston S. Millar to present his paper, *The Effective Illumination of Streets*, which brought out considerable discussion.

Thursday Morning

The Thursday morning session was devoted to the consideration of papers prepared under the auspices of the Railway Committee. Chairman D. C. Jackson of the committee, after his introductory remarks, presented an abstract of the paper by Charles H. Jones, *Unprotected Top-Contact Rail for 600-Volt Traction System*. Mr. J. V. B. Duer presented his paper, *Third-Rail and Trolley System of the West Jersey and Seashore Railroad*. The next paper, *Contact System of the Southern Pacific Company—Portland Division*, by Paul Lebenbaum, was presented, in the absence of the author, by Mr. R. F. Monges. A paper in two parts, by Messrs. E. J. Amberg and Ferdinand Zogbaum, on *Construction and Maintenance Costs of Overhead Contact Systems*, was presented by the authors. Mr. J. B. Cox presented his paper entitled *Contact System of the Butte, Anaconda and Pacific Railway*. The last paper in the series was then presented by Mr. C. J. Hixson, on *Contact Conductors and Collectors for Electric Railways*. The discussion on the whole group of papers followed.

Section Delegates

The delegates of the Sections of the Institute, together with the other members of the Sections Committee and members of the Board of Directors, met for informal discussion at luncheon on Tuesday, Wednesday and Thursday, June 29, 30 and July 1. Mr. H. A. Hornor, of Philadelphia, chairman of the Sections Committee, presided.

These meetings were exceedingly interesting to all who attended and provided an opportunity for informal discussion of many subjects relating to the welfare of the Sections, and the membership in general.

The regularly scheduled conference of officers and delegates, frequently referred to as the " experience meeting," at which each delegate reports briefly upon the activities of his Section, was held on Thursday evening, July 1. At a later date a printed report of this conference, together with a resume of the actions taken at the luncheons, will be prepared and forwarded to the delegates in attendance and to Section officers. This report will also be available, upon application to the Secretary, to any other members of the Institute who may be interested.

A complete list of the delegates present is as follows:

Atlanta	A. M. Schoen
Baltimore	John B. Whitehead
Boston	G. W. Palmer, Jr.
Chicago	E. W. Allen
Cleveland	Howard Dingle
Detroit-Ann Arbor	H. H. Norton
Fort Wayne	L. D. Nordstrum
Indianapolis-Lafayette	J. L. Wayne, 3rd
Ithaca	Frederick Bedell
Los Angeles	J. E. Macdonald
Lynn	W. H. Pratt
Madison	F. A. Kartak
Milwaukee	L. L. Tatum
Minnesota	Emil Anderson
Panama	Carl W. Markham
Philadelphia	H. F. Sanville
Pittsburgh	J. W. Welsh
Pittsfield	W. W. Lewis
Portland, Ore.	R. F. Monges
Rochester	E. L. Wilder
St. Louis	S. N. Clarkson
San Francisco	Harris J. Ryan
Schenectady	H. M. Hobart
Seattle	E. A. Loew
Spokane	D. F. Henderson
Urbana	E. B. Paine
Washington, D. C.	John H. Finney

Friday Morning

President Lincoln called the meeting to order at 10:10 o'clock, and called upon Mr. Chester L. Dawes to present his paper on *Phase Angle of Current Transformers*. He was followed by Mr. Charles L. Fortescue, who presented his paper entitled *Calibration of Current Transformers by Means of Mutual Inductances*, and the two papers were discussed together. The paper on *The Induction Watt-Hour Meter*, by V. L. Hollister, was then presented in abstract by Dr. M. G. Lloyd, and discussed. The last paper of the morning, *The Measurement of Dielectric Losses with the Cathode Ray Tube*. was presented by the author, Mr, John P. Minton.

Friday Afternoon

At the opening of the afternoon session, beginning at 2:00 o'clock, the discussion on Mr. Minton's paper was continued. When that had been completed, President Lincoln called upon Honorary Vice-President Ryan to preside during the discussion on the papers for the afternoon.

Mr. Percy W. Gumaer presented his paper, *Economic Operation of Electric Ovens*. At the close of this discussion, the final paper, *Class Rates for Electric Light and Power Systems or Territories*, by Frank G. Baum, was abstracted by Mr. H. M. Hobart. The discussion on this paper closed the session and the convention.

Entertainment

Ample entertainment features were arranged by the General Convention Committee, of which Mr. John H. Finney was chairman, and the Games Committee, of which Mr. Farley Osgood was chairman. In addition to the features specially referred to elsewhere, there were facilities for bowling, swimming, riding, and there was informal dancing each evening.

On Thursday evening, Mr. W. E. Lowes, Assistant General Passenger Agent of the Baltimore and Ohio Railroad, favored those in attendance with an illustrated historical sketch of early American railroad methods, which was of great interest to the members and ladies present.

At the meeting of the Board of Directors held on Thursday noon,

July 1, the following resolution was unanimously adopted:

Resolved, that the Board of Directors of the American Institute of Electrical Engineers hereby expresses its hearty appreciation of the services rendered by the members of the Meetings and Papers and Convention Committees in making, and carrying out with gratifying success, the plans for the 32nd Annual Convention at Deer Park, Md., June 29-July 2, 1915.

Suitable resolutions were also adopted expressing appreciation of the cooperation of the management of the Deer Park Hotel and the Passenger Department of the Baltimore and Ohio Railroad, in providing for the comfort and pleasure of the members and guests in attendance at the convention.

Baseball

The annual baseball game on Thursday afternoon, July 1, between the "Neverwases," Capt. Osgood, and the "Hasbeens," Capt. Hall, resulted in a victory for the latter by the score of 13 to 11. The large and enthusiastic audience was repaid for its attendance by the first public demonstration of many surprising innovations in the science and art of baseball.

The prizes were awarded as follows:

Longest hit: F. W. Chapman, Newbury, S. C.

Most runs: M. G. Lloyd, Chicago.

Most hits: K. D. Fisher, Huguenot Park, N. Y.

Most errors: E. H. Martindale, Cleveland.

Mr. L. T. Robinson, of Schenectady, and Prof. Dugald C. Jackson, of Boston, filled the responsible positions of umpire and official scorer, respectively, to the satisfaction of both teams, notwithstanding the strenuous efforts of partisans of the opposing forces to penetrate their strict neutrality. Only the absence of scouts from the major leagues prevented flattering offers being made to several of the players, and hence the danger of a great loss to the engineering profession was avoided.

On Thursday evening after Mr. Lowes's lecture, referred to elsewhere, Mr. H. W. Flashman, in a humorous and graceful speech in which reference was made to the successful efforts of Mr. Osgood in arranging for the entertainment and pleasure of those present, and particularly to Mr. Osgood's achievements perpetrated the same day in the baseball game, presented to Mr. Osgood, on behalf of the members, a home (dinner) plate and a fly swatter, and, on behalf of the ladies, a handsome timepiece, consisting of an alarm clock and a dog chain.

Mr. Osgood, with his usual good nature, accepted these evidences of appreciation and good will in an eminently appropriate response.

Prize Contests

The prizes for the various events were awarded as follows:

Golf. Mr. E. W. Allen, Chicago, first, (1 up, 19 holes). Mr. John R. Hewett, Schenectady, runner-up, (2 up, 1 to play). Mr. R. L. Kingsland won the consolation prize, (4 up, 2 to play).

Mr. Allen's victory entitles him to have his name inscribed on the Mershon Golf Trophy. This cup becomes the property of any person winning the golf tournament in two different years at the Institute convention. It has previously been won by Mr. A. M. Schoen, of Atlanta, and Mr. J. H. Livsey, of Detroit.

Ladies' Putting Contest. First prize was won by Mrs. C. A. Adams, of Cambridge; the second, by Mrs. N. A. Carle, of Newark, N. J.; the third, by Miss E. E. Maver, of New York.

Ladies' Card Party. Auction bridge: First, Mrs. William Maver, Jr., New York; second, Mrs. Farley Osgood, Newark, N. J.; third, Mrs. W. B. Kouwenhoven, Baltimore.

Hearts: First, Mrs. F. W. Peek, Jr., Schenectady; second, Miss Helen Lincoln, Pittsburgh.

Ladies' Bowling. First, Miss E. E. Maver, New York; second, Mrs. J. Franklin Stevens, Philadelphia.

Men's Bowling. J. W. Welsh, Pittsburgh.

Duck Pin Bowling. C. R. Underhill, New Haven, Conn.

Lucky Dancing Contest. Mrs. A. W. Berresford, Milwaukee; and Mrs. J. H. Tracy, Philadelphia.

Automobile Trip to the Convention. The prize for the longest automobile trip to the convention was awarded to Mr. Walter A. Hall, of Lynn, Mass., who was accompanied on his journey by Mrs. Hall.

Tennis. On account of rain on Friday, the last day of the convention, it was not possible to finish the tennis tournament.

Directors' Meeting, Deer Park, Md., July 1, 1915

The Board of Directors of the Institute held a meeting at Deer Park, Maryland, on July 1, during the Annual Convention.

There were present: President Paul M. Lincoln, Pittsburgh, Pa.; Vice-Presidents H. H. Barnes, Jr., New York, and Farley Osgood, Newark, N. J.; Managers C. A. Adams, Cambridge, Mass., J. Franklin Stevens, Philadelphia, Pa., P. Junkersfeld, Chicago, Ill., L. T. Robinson, Schenectady, N. Y, Frederick Bedell, Ithaca, N. Y., A. S. McAllister, New York, and John H. Finney, Washington, D. C.; Secretary F. L. Hutchinson, New York.

The action of the Finance Committee in approving monthly bills amounting to $9,034.14 was ratified.

Chairman Robinson of the Meetings and Papers Committee reported that the committee had practically completed the program for the Panama-Pacific Convention, to be held in September, and also for the meetings to be held in October in New York, Philadelphia and St. Louis.

The report of the Board of Examiners of its meeting held on June 17, was presented, and the actions taken at that meeting were approved.

Upon the recommendation of the Board of Examiners, 53 applicants were elected Associates, two applicants were elected Members, three Associates were transferred to the grade of Member, and 68 students were ordered enrolled, in accordance with the lists published elsewhere in this issue of the PROCEEDINGS.

An invitation to the Institute from the Secretary of State to appoint one delegate and an alternate to attend the Second Pan-American Scientific Congress, to be held under the auspices of the United States Government at Washington, D. C., December 27, 1915, to January 8, 1916, was presented and accepted, and the President was authorized to make appointments accordingly.

The Secretary announced the appointment by the President of Messrs. Farley Osgood, W. K. Vanderpoel and R. St. John McClelland, as representatives of the Institute to attend a conference at the Bureau of Standards, Washington, D. C., on October 27, 1915, with representatives of various organizations, for the purpose of amending, discussing and approving the National Electrical Safety Code which the Bureau has had in preparation for over a year.

A considerable amount of other business was transacted by the Board at this meeting, reference to which will be found under appropriate headings in this and future issues of the PROCEEDINGS.

Past Section Meetings

Chicago.—Election of officers for the coming year as follows—chairman, William J. Norton; secretary, Taliaferro Milton; members of executive committee, E. W. Allen, R. H. Rice and D. W. Roper.

Fort Wayne.—June 24, 1915, Fort Wayne Electric Works. Illustrated address by Mr. E. A. Wagner on "Small Transformers." Election of officers for the coming year as follows—chairman, J. J. Kline; secretary, J. J. A Snook; executive committee, E. A. Wagner, P. H. Haselton and O. B. Rinehart. Attendance 12.

Indianapolis-Lafayette.—June 29, 1915, Indianapolis. Paper: "Recent Developments in the Projection of Light," by J. W. Esterline. Election of officers for the coming year as follows—chairman, J. Lloyd Wayne; vice-chairman, C. F. Harding; secretary-treasurer, Walter A. Black; members executive committee, Charles A. Tripp and Alanson N. Topping. Attendance 20.

Los Angeles.—June 3, 1915. Election of officers for the coming year as follows—chairman, E. Woodbury; secretary, R. H. Manahan; assistant secretary, Carl Johnson; executive committee, E. F. Scattergood, R. A. Morehead, R. E. Cunningham and C. G. Pyle.

June 15, 1915, Hamburger's Cafe. Joint banquet with six other engineering societies. Short addresses by Messrs. Wm. Mulholland, James A. B. Sherer and Samuel Storrow. Attendance 200.

Madison.—June 3, 1915, Madison City Library. Papers: (1) "Some Features of the Keokuk Power Plant," by R. C. Disque; (2) "An Analysis of the Cost of Transmitting Power over the Keokuk-St. Louis Line," by Edward Bennett. Election of officers for the coming year as follows—chairman, M. C. Beebe; member of advisory board, J. N. Cadby. Attendance 28.

Milwaukee.—June 9, 1915, Plankington House. Address by Mr. L. E. Gettle on "Some Phases of the Railroad Commission Work." Election of officers as follows—chairman, R. B. Williamson; secretary, H. P. Reed. Attendance 85.

Minnesota.—June 11, 1915, Duluth, Minn. Papers: (1) "The Power Development at Thompson, Minn.," by W. N. Ryerson; (2) "The Iron Ore Industry of Minnesota," by J. H. Hearding. After the technical program the party was taken by boat to visit coal and ore docks at Duluth—Superior and also inspected the new steel plant. Attendance 125.

Philadelphia.—June 14, 1915. Hotel Walton. Annual dinner of Section; short addresses by Messrs. H. F. Sanville, George Ross Green, F. L. Hutchinson, Ralph W. Pope, J. H. Tracy, H. A. Hornor, D. C. Jackson, A. W. Berresford, Farley Osgood, Paul Spencer, H. Clyde Snook, Clayton W. Pike and Dr. Crampton. Election of officers for the ensuing year as follows—chairman, J. H. Tracy; managers, H. P. Liversidge, Harold Pender and M. G. Kennedy; secretary-treasurer, W. F. James; assistant secretary, Charles Penrose. Attendance 124.

Pittsburgh.—June 15, 1915, Oliver Building. Illustrated addresses on "The Panama-Pacific Exposition," by A. A. Hamerschlag and A. W. Tarbell. Election of officers for the coming year as follows—chairman, T. H. Schoepf; secretary-treasurer, G. C. Hecker; executive committee, W. Dudley, J. W. Welsh, C. R. Riker, A. G. Pierce, L. H. Harris, W. T. Snyder and Bernard Lester. Attendance 70.

Spokane.—May 21, 1915, Silver Grill. Election of officers for the ensuing year as follows—chairman, V. H. Greisser; vice-chairman, D. F. Henderson; secretary, C. A. Lund; executive committee, J. W. Hungate, J. B. Fisken, H. B. Peirce and L. N. Rice. Attendance 33.

Vancouver.—April 30, 1915, Metropolitan Building. Paper: "Some Industrial Power Applications from a Central Station Viewpoint," by E. Holder. Attendance 15.

May 28, 1915, Metropolitan Building. Election of officers for the coming year as follows—chairman, R. F. Hayward; secretary, K. A. Auty. Paper: "Electricity as Applied to Metallurgy and Mining Generally, and Its Economic Advantages," by E. A. Haggan. Attendance 13.

Past Branch Meetings

University of Missouri.—April 26, 1915, Engineering Building. Lecture by Mr. C. C. Boswell on "Panama Canal Control," illustrated by moving pictures. Attendance 25.

May 11, 1915, Engineering Building.

Paper: "Steel Mill Electrification," by B. O. Wiley, illustrated by lantern slides. Attendance 35.

May 24, 1915, Engineering Building. Election of officers for the coming year as follows—chairman, Kerr Atkinson; secretary, E. W. Kellogg; vice-chairman, D. S. Foster; treasurer, C. C. Boswell; assistant secretary, S. H. Anderson; corresponding secretary, C. P. Meyer. Attendance 13.

Personal

Mr. L. Jorgensen, who for the past eight years has been associated with the engineering firm of F. G. Baum and Company, of San Francisco, has resigned from that company and will hereafter engage in general electric and hydraulic engineering practise, specializing in the design of arch dams. Mr. Jorgensen will have an office at 1405 Chronicle Building, San Francisco, Cal.

Mr. Edwin G. Hatch, consulting engineer, New York, will handle the tests and inspection of a 9000-kv-a. transformer for the Victoria Falls and Transvaal Power Company of London, now in course of construction at the Westinghouse works, East Pittsburgh, Pa. Five similar transformers were shipped to the company's plant in South Africa in 1912.

Mr. George A. Balling has resigned from the service of the Panama Canal Commission, and is enjoying a vacation at his home in Chicago. Mr. Balling was in charge of the installation of electrical equipment at Gatun and was responsible for the development of a great many labor and time saving devices which permitted this work to be completed in the short time allotted. Previous to his employment with the Canal Commission, Mr. Balling was in charge of construction work for the Commonwealth Edison Company in Chicago and the General Electric Company in Mexico.

Mr. Joseph Shepherd has terminated his engagement as electrical engineer for the London County Council Tramways, to continue, under the name of Shepherd and Watney, the practise of consulting engineer carried on during the past twenty-four years by Mr. T. S. Watney at 32 Greek Street Chambers, Park Row, Leeds, and also at 47 Queen Anne's Chambers, Westminster, England. Mr. Shepherd for fifteen years held responsible positions with leading manufacturing companies, turning out practically every type of electrical and other plant, and for the past thirteen years has been with the London County Council Tramways Department—for eight years as chief assistant electrical engineer, and since 1910 in entire charge of the electrical work of the undertaking, with an annual output of 150 million kw-hr., larger than that of any other municipal undertaking in the world. Mr. Shepherd expects to make the inspection of plant a feature of his future work. Mr. Watney will continue his interest in the practise in an advisory capacity.

Recommended for Transfer, August 4, 1915

The Board of Examiners, at its regular monthly meeting on August 4, 1915, recommended the following members of the Institute for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the Secretary.

To Grade of Member

Biesecker, Arthur S., Electrical Engineer, Scranton Electric Construction Co., Scranton, Pa.

Boyce, Frank G., Chief Operator and Supt. Power Plant Maintenance, Milwaukee Electric Railway & Light Co., Milwaukee, Wis.

Enfield, William L., Manager Special Engineering Dept., National Lamp Works of General Electric Co., Nela Park, Cleveland, O.

HILL, GUY, Expert Radio Aid, Machinery Division, Navy Yard, Brooklyn, N. Y.

KLAUBER, LAURENCE M., Supt. of Electric Dept., San Diego Consolidated Gas & Electric Co., San Diego, Cal.

LUCKIESH, M., Physicist, Nela Research Laboratory, National Lamp Works of General Electric Co., Nela Park, Cleveland, O.

LYNN, SCOTT, Manager Rochester District Office, Sangamo Electric Co. of Springfield, Ill., Rochester, N. Y.

RANKIN, FRED J., Electrical Engineer, Public Utilities Commission of Colorado, Denver, Colo.

Transferred to the Grade of Member July 1, 1915

The following Associates were transferred to the grade of Member of the Institute at the meeting of the Board of Directors on July 1, 1915.

HAZELTON, HUGH, Electrical Engineer, New York, N. Y.

NICHOLS, HAROLD E., Engineer, Research Branch, Western Electric Co., New York, N. Y.

RUEL, AMAI J., Electrical Engineer, Northern Idaho & Montana Power Co., Sandpoint, Idaho.

Members Elected July 1, 1915

HARROLD, ALFRED EMIL, Special Engineer, Willard Storage Battery Co., Cleveland, Ohio.

HIRSCH, GUSTAV, Consulting Engineer, 274 S. Third St.; res., 956 Jaeger St., Columbus, Ohio.

Associates Elected July 1, 1915

ADAIR, WILLIAM R., Master Mechanic, Pittsburgh and Butler Ry. Co., Mars, Pa.

ATKINSON, GEORGE W., Electrical Engineer, Supervising Architect's Office, Treasury Dept.; res., 1503 Que St. N. W., Washington, D. C.

BANZHOF, CHARLES P., Staff Engineer and Superintendent, Fidelity Electric Co.; res., 508 N. Plum St., Lancaster Pa.

BEALL, FRANK H., Assistant in Electrical Engineering, Graduate School of Applied Science, Harvard University, Cambridge, Mass.

BENJAMIN, LOUIS S., Engineer in charge, Mechanical and Electrical Dept., Atlantic Sugar Refineries, Ltd., St. John, N. B.

BENNEY, GEORGE ANDREW, President, Benolite Co., 331 Fourth Ave., Pittsburgh, Pa.

BENSON, CHENERY F., Station Electrician, Electrical Dept., Swift & Co.; res., 4646 Indiana Ave., Chicago, Ill.

BRADLEY, HARRY L., Manager and Secretary, Allen-Bradley Co., 495 Clinton St., Milwaukee, Wis.

BROPHY, JOHN J., Electrician, Turner Tanning Machinery Co., Peabody; res., Salem, Mass.

CAIGAN, ISRAEL, Engineer, R. D. Kimball Co., Boston; res., 24 Canterbury St., Dorchester, Mass.

CLARK, FRED H., Division Plant Supervisor, Mountain States Tel. & Tel. Co., Salt Lake City, Utah.

COLE, KENNETH E. N., Salesman, General Electric Co., St. Louis, Mo.; res., 612 Beach St., Little Rock, Ark.

DAILEY, JOHN B., Experimental Laboratory, Ford Motor Co.; res., 111 Leicester Court, Detroit, Mich.

DAVIS, JOHN MORTON, Purchasing Agent, General Electric Co., West Lynn; res., 104 Federal St., Salem, Mass.

DE ANGELIS, MARIO LEWIS, Engineer, Cie. F'se. Thomson-Houston; res., 119 Avenue Mozart, Paris, France.

DUKE, HENRY TRISDOM, JR., Assistant Engineer, Ballinger and Perrot; res., 5536 Elliott St., Philadelphia, Pa.

EDWARDS Y SUTIL, RAFAEL, Civil and Electrical Engineer, Calle Apertinas No. 1170, Santiago, Chile, S. A.

FERGUSON, GEORGE F., Superintendent, Addington Sub-station, Lake Coleridge Hydro-Electric Scheme, Christchurch, New Zealand.

GURDES, FRED A., Chief Electrical Operator, Electrical Dept., Commissioners of Lincoln Park, Chicago, Ill.

HACKER, GUSTAV, III Kegelgasse 43, Vienna, Austria.

HEWITT, ARTHUR CHALLIS, Electrical and Mechanical Engineer, Security Cement & Lime Co., Hagerstown, Md.

HONEGGER, ARNOLD, Representative, Wseobschtschaja Kompania Elektritschestwa, Petrograd, Russia, c/o General Electric Co., Schenectady, N. Y.

HORNBACK, F. S., Engineer, Calgary Petroleum Products Co., Black Diamond, Alberta, Canada.

HORTON, ROY S., Manager, Oakland Office, Dalton, Adding Machine Co., Oakland; res., 2634 Bancroft Way, Berkeley, Cal.

*INAGAKY, TADA-YOSHI, Draftsman, Columbus Railway, Power & Light Co.; res., 1066 Neil Ave., Columbus, Ohio.

*IRVIN, RALPH, Treasurer and Manager, Salmon River Power & Light Co., Salmon, Idaho.

IRVINE, THOMAS FRANCIS, Plant Inspector, Central District Tel. Co., 1120 Schmulbach Bldg., Wheeling, W. Va.

IRWIN, HOWARD W., Investigating Engineer, Motive Power & Machinery Dept., Bay State Street Ry. Co., 84 State St., Boston, Mass.

JACOBI, EDWARD NICHOLAS, Electrical Designer and Assistant Engineer, Briggs & Stratton Co.; res., 712 5th St., Milwaukee, Wis.

KIMBALL, CHARLES B., Engineering Dept., General Electric Co., Boston; res., 134 Prospect Ave., Wollaston, Mass.

KNOST, CHARLES P., Chief Electrician, Care Ernestine Mining Co., Mogollon, Socorro Co., New Mexico.

*KROTZER, F. W., Instructor of Electricity, Central Continuation School; res., Y. M. C. A., 4th St., Milwaukee, Wis.

LAMOTTE, WILLIAM R., Engineering Dept., Public Service Electric Co., Newark; res., 236 7th St., Jersey City, N. J.

LILJENROTH, FRANS GEORG, Chief Engineer, Allmanna Svenska Electric Co., Vesteras, Sweden.

LINDSAY, HENRY D., Engineer, Allen-Bradley Co.; res., 258 Farwell Ave., Milwaukee, Wis.

LINDSTROM, N. GUSTAV G., Chief Engineer, Electric Products Co.; res., 516 E. 108th St., Cleveland, Ohio.

LYTLE, LLOYD B., Electrician, Consolidated Mining & Smelting Co., Rossland, B. C.

*MACBURNEY, J. LOGAN, Engineering Dept., Electric Storage Battery Co.: res., 2625 N. 33rd St., Philadelphia, Pa.

MAINLAND, JAMES, Chief Electrician, U. S. Coal & Oil Co., Holden, W. Va.

*MALMBORG, CARL A., Superintendent, Lehigh Municipal Water & Light Plant, Lehigh, Iowa.

MOORE, DAVID H., Asst. Engineer, Transformer Testing Dept., General Electric Co.; res., 54 Stratford Ave., Pittsfield, Mass.

OWENS, EDWARD T., Signal Foreman, The Panama Canal, Balboa Heights, Canal Zone.

PEAKE, KENNETH C., Engineering Dept., Public Service Electric Co.; res., 288 Johnson Ave., Newark, N. J.

*PHILBRICK, JOHN S., Shift Engineer, Marconi Trans-Pacific Wireless Telegraph Station, Bolinas, Cal.

ROSS, ROBERT HALLIDAY, Chief Electrical Engineer, Mt. Bischoff Tin Mining Co., Waratah, Tasmania.

SARGENT, PERCY G., District Plant Chief, American Tel. & Tel. Co., 518 No. Beaumont St., St. Louis, Mo.

SCHLUTER, WILHELM H. F., Inspection Duty, Ordnance Dept., U. S. Navy; res., 3715 Avenue I, Brooklyn, N. Y.

SEMMES, LARALETTE D., Morgan & West Box Co., Madison, Ark.

VICKERS, CHAUNCEY H., Draftsman, Commissioners of Lincoln Park; res., 4752 Prairie Ave., Chicago, Ill.

WALDRON, GILBERT T., Electrical Contractor, 1033 Park St., Peekskill, N.Y.

WHITE, CHARLES D., Boston Representative, Metropolitan Electric Mfg. Co., 146 Summers St., Boston, Mass.

WHITING, HAROLD R., Superintendent, Cavite Water Power, Porto Rico Irrigation Service, Guayama, Porto Rico.

WRENCH, ROBERT A., Electrical Foreman, Braden Copper Co., Rancagua, Chile, S. A.

Total 53.

*Former enrolled students.

Applications for Election

Applications have been received by the Secretary from the following candidates for election to membership in the Institute. Unless otherwise indicated the applicant has applied for admission as an Associate. If the applicant has applied for direct admission to a higher grade than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the Secretary before August 31, 1915.

Almquist, F. G. (Member), New York.
Balfe, R. M., Vancouver, B. C.
Beal, R. R., Palo Alto, Cal.
Belt, T. A. E., Schenectady, N. Y.
Bennett, C. E. (Member), Waterbury, Conn.
Bowles, J. D., Jefferson City, Mo.
Branson, E. H., Pittsfield, Mass.
Brooks, M. J., Heyden, Ariz.
Burton, H. R., Thorold, Ont.
Bush, V., East Elmhurst, L. I.
Calland, O. G., Barberton, Ohio.
Cook, C., Lindale, Ga.
Craigue, N. A., City Point, Va.
Danley, R. J. M. (Fellow), Brooklyn, N. Y.
Darling, A. G., Duluth, Minn.
Duer, J. Van B., Altoona, Pa.
Erb, W., Jr., Philadelphia, Pa.
Ferrari, C., Naples, Italy.
Flach, O. C., Wilkinsburg, Pa.
Furnas, W. C., West Allis, Wis.
Gallaher, S. M., Charleston, W. Va.
Goetz, J. A., Oakland, Cal.
Grimes, W. F., Jr., Balboa Heights, C.Z.
Hall, H. S., Brooklyn, N. Y.
Harding, E. R., Chicago, Ill.
Hart, A. L., Milwaukee, Wis.
Hastings, A. A., Napier, N. Z.
Hausamann, G. J., West Hoboken. N. J.
Helliesen, H. L., Kristiana, Norway.
Hetherington, W., Jr., New York, N. Y.
Hooper, A. G., Schenectady, N. Y.
Hunter, T. M., Newark, N. J.
Jackson, D. A., Newcastle, B. C., Can.
Jansson, G. E., Schenectady, N. Y.
Jones, R. E., Toronto, Ontario.
Kazaoka, K., Schenectady, N. Y.
Kierstead, F. H., Pittsfield, Mass.
Kubanyi, V. J., New York, N. Y.
Lamar, R. W., Sault Ste. Marie, Ont.
Lewis, J. V., Schenectady, N. Y.
Lorch, A., Brooklyn, N. Y.
McCarthy, W. M., New York, N. Y.
McCormick, I. E., McCormick, Wash.
Mellen, P., Chicago, Ill.
Montcalm, S. R., Charleston, S. C.
Nakamigawa, T., Schenectady, N. Y.
Parkinson, R.W., Maracaibo, Venezuela.
Pilkington, E. J., Waterbury, Conn.
Ramsay, J. A., El Paso, Texas.
Robison, C. D. (Member), New York, N. Y.
Roosevelt, G. H., Dawson City, Y. T.
Ruttiman, A., Menominee, Mich.
Scarburgh, R. S., New York, N. Y.
Segel, H., Pittsfield, Mass.
Shute, L. H., Denver, Colo.
Simmons, A. L., Fresno, Cal.
Smith, J. A., Addington, Christchurch, N. Z.
Stockwell, R. K., Rancagua, Chile, S. A.
Sugden, J., Schenectady, N. Y.
Swingle, C. W., Halfway, Ore.
Thomsen, C. A., St. Timothee, Quebec.
Tompkins, H. K.V., Greeneville, Tenn.
Troxell, H. LaR., Pine Grove, Penn.
Turner, E. P. (Member), Christchurch, N. Z.
Warwick, J. F., Atlanta, Ga.
Wedderspoon, W.C., Christchurch, N.Z.
Whitaker, G., London, E. C., Eng.
Williams, A. F., Barcelona, Spain.
Wilson, A. B., Plainfield, N. J.
Woolhiser, H. L., Boston, Mass.

Total 70.

Students Enrolled July 1, 1915

7373 Flynn, F. K., Stanford Univ.
7374 Navy, E. R., Worcester Poly. Inst.
7375 Bergman, D. J., Univ. of Calif.
7376 Dana, A. S., Mass. Institute Tech.
7377 Connors, H. E., De Paul Univ.
7378 Deiss, W. C., Univ. of Illinois.
7379 Oakes, C. E., Ore. Agri. College.
7380 Allen, G. Y., Stevens Inst. Tech.
7381 Wood, E. E., Yale University.
7382 Middleton, E. W., Purdue Univ.
7383 Haberkorn, T. E., Purdue Univ.
7384 Booth, G. E., Univ. of Wisconsin.
7385 Elsasser, H. W., Columbia Univ.
7386 Wickersham, R. C., Lehigh Univ.
7387 Sweeny, P. J., Univ. of Illinois.
7388 Brunner, H. H., Colorado College.
7389 Hardin, R. S., Univ. of Wis.
7390 Searson, R.G., Carnegie Inst. Tech.
7391 Rehman, N. J., Bucknell Univ.
7392 Davis, M. A., Stevens Institute.
7393 Luck, J. M., Univ. of Virginia.
7394 Hermann, R. L., Univ. of Illinois.
7395 Thatcher, G. R., Univ. of N. D.
7396 Wakefield, H., Univ. of N. D.
7397 Grady, J. M., Villanova College.
7398 Hoffman, H. C., Drexel Institute.
7399 Autrobus, E. R., Drexel Inst.
7400 Young, L. R., Drexel Institute.
7401 Alexander, C. F., Worcester Polytechnic Institute.
7402 Aiken, F., Worcester Poly. Inst.
7403 Snyder, W., Jr., Rensselaer Polytechnic Institute.
7404 Hinchliffe, T. W., Rensselaer Polytechnic Institute.
7405 Woodworth, E. L., Rensselaer Polytechnic Institute.
7406 Shaffer, S., Armour Inst. Tech.
7407 Berwald, C. H., Univ. of Illinois.
7408 James, E. A., Univ. of Illinois.
7409 Eaton, F. W., Worcester Poly. Inst.
7410 Schroeder, C. W., Univ. of Minn.
7411 O'Leary, J. A., Villanova College.
7412 Pride, A. W., Worcester Poly. Inst
7413 Grasle, W. R., Ore. Agri. College.
7414 Carmichael, E. T., Lehigh Univ.
7415 Crittenden, R. E., Worcester Polytechnic Institute.
7416 Ries, C., Ohio Northern Univ.
7417 Strauch, W., Villanova College.
7418 Gilchrist, L. F., Villanova, College
7419 Windsor, C. C., Columbia Univ.
7420 Barrows, A. S., Worcester Polytechnic Institute.
7421 Conard, F. U., Stevens Inst. Tech.
7422 Shanck, R. B., Ohio State Univ.
7423 Cowle, H. H., Ohio State Univ.
7424 Sherrerd, G., Jr., Case School of Applied Science.
7425 McGilvary, L. P., Univ. of Wis.
7426 Zimmerman, C. D., Rensselaer Polytechnic Institute.
7427 Lehnhoff, R. G., Univ. of Cin.
7428 Baker, E., Univ. of Texas.
7429 Page, E. W., Rensselaer Poly. Inst.
7430 Eleazarian, A. M., Univ. of Ill.
7431 Ray, B. C., Univ. of Illinois.
7432 Rifenburg, R. C., Rensselaer Polytechnic Institute.
7433 Felton, S. M., Harvard University
7434 Sawyer, L. G., Univ. of Maine.
7435 Hurst, H. A., Ohio Northern Univ.
7436 Warner, E. E., Univ. of Illinois.
7437 Keller, C. C., Ohio State Univ.
7438 Murphy, J. C., Jr., Villanova Coll.
7439 Wilder, P. W., Univ. of Wisconsin.
7440 Martin, DeL. K., Poly. Coll. Engg.

Total 68

EMPLOYMENT DEPARTMENT

NOTE: Under this heading brief announcements (not more than 50 words in length) of vacancies, and men available, will be published without charge to members. Copy should be prepared by the member concerned and should reach the Secretary's office prior to the 20th of the month. Announcements will not be repeated except upon request received after an interval of three months; during this period names and records will remain in the office reference files. All replies should be addressed to the number indicated in each case, andm ailed to Institute headquarters.

The cooperation of the membership by notifying the Secretary of available positions, is particularly requested.

Vacancies

V-71. Position open for an American-born electrical engineer, university graduate, one having had considerable experience designing modern interpole direct-current motors and generators. Send reference that will stand thorough investigation. All replies considered confidential.

The United States Civil Service Commission announces open competitive examinations for junior engineer (civil) and junior engineer (mechanical or electrical) on August 25 and 26, 1915, at numerous places in the United States.

The Manual of Examinations for the Fall of 1915 provides that applicants for these examinations must have had at least five years good experience in civil (or mechanical or electrical) engineering work, and that graduation in civil (or mechanical or electrical) engineering from any technical school of recognized standing will be considered equivalent to three and one-half years of this period. Attention is invited to the fact that the requirements have now been reduced to four years good civil (or mechanical or electrical) engineering experience, or graduation in civil (or mechanical or electrical) engineering from an approved technical school. Both married and unmarried men will be admitted to these examinations.

From the register of eligibles resulting from these examinations selections may be made to fill vacancies arising in the grade of junior engineer in the Engineer Department at Large. The examinations are, however, held primarily to enable applicants to qualify for the examination to be held by the War Department on or about October 25, 1915, for commissions as second lieutenants in the Corps of Engineers, United States Army. Of those who attain eligibility in one of these examinations only those who meet the following conditions will be permitted to take the examination given by the War Department: They must be (a) unmarried, (b) between 21 and 29 years of age, and (c) graduates in an engineering course from an approved technical school.

Persons who meet the requirements and desire these examinations should at once apply for the circular announcing this examination (Form No. 638, issued July 22, 1915) and Form No. 1312, stating the title of the examination for which the form is desired, to the United States Civil Service Commission, Washington, D. C. Application forms may also be obtained from the Secretary of the U. S. Civil Service Board at any of the places where the examination will be held, and if it appears to an applicant desiring this examination that it will not be possible to obtain the necessary forms from the Commission at Washington in time, it is suggested that inquiry be made at the nearest post office or custom house.

Men Available

316. Civil Engineer. Age 29. Six years' experience in location, design and construction of underground conduits, four to forty ducts, reinforced concrete and waterproof construction. Entire charge of this work at present for large street railway system. Available at short notice.

317. Technical Graduate, (1909), married. Five years' experience as foreman, inspector, draftsman and chief inspector on railroad electrification work. Can handle men, make estimates and draw up designs. Proficient on catenary work. Location immaterial.

318. Electrical Engineer. Age 31. Twelve years' experience; five years in charge of hydroelectric installations totaling over 120,000 kw.; two years in charge of construction and maintenance for one of the largest U. S. copper mining companies. At present employed; desires change, Mexico or South America preferred.

319. Sales Engineer. Mechanical and electrical engineer, technical graduate, with long practical experience in design, construction and operation of central stations and railway systems, and selling of large apparatus, would like to become connected with Chicago office of manufacturing company, in sales or production departments.

320. Manager or Superintendent. Mem. A. I. E. E., age 44. Twenty years' experience as chief engineer and superintendent of large central stations; has successful record. Open for immediate engagement in above line of work or other special work requiring experience and executive ability to obtain results.

321. Electrical Engineer. Age 30. Desires position as superintendent for electric light and power company in small town, or with consulting engineer. Experienced in power and substation design and construction, also in transmission and distribution systems. At present engaged with electric light company.

322. Mr. Manager: An Associate of the Institute wants a job. In the contracting business for himself seven years; past two years building substations, improving regulation of hydroelectric plants. Proficient at emergency work and would be very valuable where construction is to be done in out-of-the-way places. Write him and tell him what you want done.

323. Electrical Engineer. Technical graduate; age 25; married. Desires position with progressive interurban electric railway, or with steam railroad intending to electrify in the near future. One year's experience in shop and test department and three years' experience in engineering department of large electrical manufacturing company.

324. Graduate Electrical Engineer. Age 33, married. Engineering apprentice and erecting engineer; estimating, designing, purchasing and erection of steam and hydroelectric stations, substations, and transmission lines up to 120,000 volts. Some work on valuation. Available about October 1.

325. Electrical Engineer, with extensive experience in power plant and motor application work, desires position as superintendent of power plant, district superintendent or commercial engineer. Familiar with the latest practise and up-to-date apparatus. Would prefer location in a small or medium size city.

326. Electrical Engineer of industrial organization with 14,000-kw. plant wishes to return to Spanish-speaking country. Prefers position in charge of construction with a view to remaining as superintendent of power. Experience embraces: 110,000-volt and low-tension transmission, distribution and stations, telephones, magneto; ice plants, compression, large welding and electrolytic installations. An excellent handler of men; speaks Spanish fluently.

327. Electrical Engineer, Cornell graduate, desires position with consulting engineer or contractor on layout or installation of equipment in factories and office buildings. New York City or vicinity preferred. Three and a half years' experience, including testing, design, installation and operation of switchboards, wiring and machinery.

328. Electrical-Mechanical Engineer (Degree B.E. 1907). Eight years' experience, covering 2½ years G. E. Co. testing and engineering. Later experience includes steam turbine and hydroelectric plants of large capacity; distribution and transmission systems up to 110,000 volts. Past duties include designing, superintending construction, operation, reports on properties and sales engineering.

329. Assistant Electrical Engineer, technical graduate, five years'experience in the supervision of electrical work. Desires position in New York City. Moderate salary.

330. Technical Graduate (E.E.), single, total abstainer from alcohol, tobacco and drugs, with 4½ years' experience in mechanical and electrical drafting and care of apparatus, and several years business experience outside of engineering lines, desires position in electrical engineering work. Available at once. Salary to start secondary.

331. Vacuum tube specialist, several years' experience each in general electrical investigations and in engineering connected with vacuum tube manufacture.

332. Electrical and Mechanical Engineer, with exceptional technical and commercial experience in designing, constructing, operating and contracting work on public utilities, electrifications and modern steam power plants; familiar with domestic and foreign practise and apparatus. Desires responsible position with reliable concern. Engaged as power expert and purchasing agent past few years. Speaks several languages.

Library Accessions

The following accessions have been made to the Library of the Institute, since the last acknowledgment.

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United Engineering Society

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Formeln und Tabellen für den Eisenbau. By Freidrich Bleich Wien, 1915. (Purchase.)

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Jute and Linen Weaving. By Thomas Woodhouse and Thomas Milne. London, 1914. (Purchase.)

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Practical Coal Mining. Ed. 5. By George L. Kerr. London, 1914. (Purchase.)

Railway Economics. A collective catalogue of books in fourteen American libraries. Chicago, n.d. (Gift of Bureau of Railway Economics.)

Screw Cutting in the Lathe. By E. G. Barrett. London, 1912. (Purchase.)

Selenium in the Production of Colored Glass. By Samuel Wein. (Reprinted from Scientific American, Apr. 17, 1915.) n.p. n.d. (Gift of author.)

Sheet Metal Working. By F. Georgi and A. Schubert, translated from the German by Chas. Salter. London, 1914. (Purchase.)

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Straight Line Engineering Diagrams. By Manifold and Poole. San Francisco, n.d. (Purchase.)

Structural Engineers' Handbook. By M. S. Ketchum. New York, 1914. (Purchase.)

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Text-book of Physics. vol. III, Ed. 4—Heat. By J. H. Poynting and J. J. Thomson. London, 1911. (Purchase.)

——Vol. I, Ed. 6—Properties of Matter. By J. H. Poynting and J. J. Thomson. London, 1913. (Purchase.)

Tonindustrie Kalender, pts. 1-3, 1915. Berlin, 1915. (Gift of Tonindustrie Zeitung.)

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Leonardo da Vinci. Il Codice di della Biblioteca di Lord Leicester in Holkjam Hall. Milano, 1909. (Purchase.)

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Who's Who in Mining & Metallurgy, 1910. London, 1910. (Purchase.)

Woodworking Machinery. Ed. 3. By M. P. Bale. London, 1914. (Purchase.)

Zone Plan of Refuse Disposal, material describing. (Gift of Mrs. Flora Spiegelberg & Mr. H. Liebau.)

OFFICERS AND BOARD OF DIRECTORS, 1915-1916

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(Term expires July 31, 1916.)
JOHN J. CARTY.

JUNIOR PAST-PRESIDENTS.

(Term expires July 31, 1916.)
C. O. MAILLOUX.

(Term expires July 31, 1917.)
P. M. LINCOLN.

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FARLEY OSGOOD.

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(Term expires July 31, 1916.)

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HONORARY VICE-PRESIDENT
(on the Pacific Coast during Panama-Pacific Exposition.)
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LIBRARIAN.
W. P. CUTTER.

GENERAL COUNSEL.
PARKER and AARON,
52 Broadway, New York.

PAST PRESIDENTS.—1884-1915.

*NORVIN GREEN, 1884-5-6.
*FRANKLIN L. POPE, 1886-7.
T. COMMERFORD MARTIN, 1887-8.
EDWARD WESTON, 1888-9.
ELIHU THOMSON, 1889-90.
*WILLIAM A. ANTHONY, 1890-91.
ALEXANDER GRAHAM BELL, 1891-2.
FRANK JULIAN SPRAGUE, 1892-3.
*EDWIN J. HOUSTON, 1893-4-5.
LOUIS DUNCAN, 1895-6-7.
FRANCIS BACON CROCKER, 1897-8.
A. E. KENNELLY, 1898-1900.
CARL HERING, 1900-1.
CHARLES P. STEINMETZ, 1901-2.
CHARLES F. SCOTT, 1902-3.
BION J. ARNOLD, 1903-4.
JOHN W. LIEB, 1904-5.
SCHUYLER SKAATS WHEELER, 1905-6.
SAMUEL SHELDON, 1906-7.
HENRY G. STOTT, 1907-8.
LOUIS A. FERGUSON, 1908-09.
LEWIS B. STILLWELL, 1909-10.
DUGALD C. JACKSON, 1910-11.
GANO DUNN, 1911-12.
RALPH D. MERSHON, 1912-13.
C. O. MAILLOUX, 1913-14.
PAUL M. LINCOLN, 1914-15.

*Deceased.

LIST OF SECTIONS

Revised to Aug. 1, 1915.

Name and when Organized		Chairman	Secretary
Atlanta	Jan. 19, '04	A. M. Schoen	H. M. Keys, Southern Bell Tel. & Tel. Co., Atlanta, Ga.
Baltimore	Dec. 16, '04	J. B. Whitehead	L. M. Potts, Industrial Building, Baltimore, Md.
Boston	Feb. 13, '03	L. L. Elden	Ira M. Cushing, 84 State St., Boston, Mass.
Chicago	1893	W. J. Norton,	Taliaferro Milton, 613 Marquette Building, Chicago, Ill.
Cleveland	Sept. 27, '07	E. H. Martindale	Ralph Beaman, Cleveland, Ohio.
Denver	May 18, '15	W. A. Carter	Robert B. Bonney, Mountain States Tel. and Tel. Co., Denver, Colo.
Detroit-Ann Arbor	Jan. 13, '11	Ralph Collamore	C. E. Wise, 427 Ford Bldg, Detroit, Mich.
Fort Wayne	Aug. 14, '08	J. J. Kline	J. J. A. Snook, 927 Organ Avenue, Ft. Wayne, Ind.
Indianapolis-Lafayette	Jan. 12, '12	J. L. Wayne, 3rd	Walter A. Black, 3042 Graceland Ave., Indianapolis, Ind.
Ithaca	Oct. 15, '02	E. L. Nichols	W. G. Catlin, Cornell Univ., Ithaca, N. Y.
Los Angeles	May 19, '08	E. Woodbury	R.H. Manahan, 32 City Hall, Los Angeles, Cal.
Lynn	Aug. 22, '11	G. N. Chamberlin	F. S. Hall, General Electric Co., Lynn, Mass.
Madison	Jan. 8, '09	M. C. Beebe	F. A. Kartak, Univ. of Wisconsin, Madison, Wis.
Mexico	Dec. 13, '07		
Milwaukee	Feb. 11, '10	R. B. Williamson	H. P. Reed, Cutler-Hammer Mfg. Co., Milwaukee, Wis.
Minnesota	Apr. 7, '02	E. T. Street	Walter C. Beckjord, St. Paul Gas Light Co., St. Paul, Minn.
Panama	Oct. 10, '13	William H. Rose	C. W. Markham, Balboa Heights, C. Z.
Philadelphia	Feb. 18, '03	J. H. Tracy	W. F. James, 1115 North American Bldg., Philadelphia, Pa.
Pittsburgh	Oct. 13, '02	T. H. Schoepf,	G. C. Hecker, 436 Sixth Avenue, Pittsburgh, Pa.
Pittsfield	Mar. 25, '04	M. O. Troy	F. R. Finch, General Electric Company, Pittsfield, Mass.
Portland, Ore.	May 18, '09	R. F. Monges	Paul Lebenbaum, 45 Union Depot, Portland, Ore.
Rochester	Oct. 9, '14	E. L. Wilder	F. E. Haskell, Mechanics Institute, Rochester, N. Y.
St. Louis	Jan. 14, '03	S. N. Clarkson	W. O. Pennell, Southwestern Bell Tel. System, St. Louis, Mo.
San Francisco	Dec. 23, '04	C. J. Wilson	A. G. Jones, 811 Rialto Building, San Francisco, Cal.
Schenectady	Jan. 26, '03	L. T. Robinson	F.W. Peek, Jr., Gen. Elec. Co., Schenectady, N. Y.
Seattle	Jan. 19, '04	S. C. Lindsay	E. A. Loew, University of Washington, Seattle, Wash.
Spokane	Feb. 14, '13	Victor H. Greisser	C. A. Lund, Washington Water Power Co., Spokane, Wash.
Toledo	June 3, '07	George E. Kirk	Max Neuber, Cohen, Friedlander & Martin, Toledo, Ohio.
Toronto	Sept. 30, '03	D. H. McDougall	H. T. Case, Continental Life Building, Toronto, Ontario.
Urbana	Nov. 25, '02	I. W. Fisk	P. S. Biegler, Univ. of Illinois, Urbana, Ill.
Vancouver	Aug. 22, '11	R. F. Hayward	K. A. Auty, B. C. Electric Railway Co., Ltd., Vancouver, B. C.
Washington, D. C.	Apr. 9, '03	R. H. Dalgleish	Arthur Dunlop, National Electric Supply Company, Washington, D. C.

Total 32

LIST OF BRANCHES

Name and when Organized		Chairman	Secretary
Agricultural and Mech. College of Texas	Nov. 12, '09	J. F. Nash	A. Dickie, A. & M. College, College Station, Texas
Alabama, Univ. of	Dec. 11, '14	W. M. Johnston	L. M. Smith, University, Ala.
Arkansas, Univ. of	Mar. 25, '04	P. X. Rice	F. M. Ellington, University of Arkansas, Fayetteville, Ark.
Armour Institute	Feb. 26, '04	W. L. Burroughs	Chester F. Wright, 3341 Michigan Boulevard, Chicago, Ill.
Bucknell University	May 17, '10	N. J. Rehman	E. C. Hageman, Bucknell University, Lewisburg, Pa.
California, Univ. of	Feb. 9, '12	J. V. Kimber	H. A. Mulvaney, 1521 Hopkins Street, Berkeley, Cal.
Cincinnati, Univ. of	Apr. 10, '08	F. Oberschmidt	A. C. Perry, 707 East McMillan Street, Cincinnati, O.
Clemson Agricultural College	Nov. 8, '12	W. E. Blake	F. L. Bunker, Clemson College, S. C.
Colorado State Agricultural College	Feb. 11, '10	G. M. Strecker	E. O. Marks, Colorado State Agricultural College, Fort Collins, Colo.

LIST OF BRANCHES—Continued.

Name and when Organized.	Chairman	Secretary.
Colorado, Univ. of...... Dec. 16, '04	E. F. Peterson	Samuel J. Blythe, University of Colorado., Boulder, Colo.
Georgia School of Technology.............. June 25, '14	R. A. Clay	J. M. Reifsnyder, Jr., Georgia School of Technology, Atlanta, Ga.
Highland Park College..Oct. 11, '12	Clyde Prussman	Ralph R. Chatterton, Highland Park College, Des Moines, Iowa.
Idaho, Univ. of........ June 25, '14	E. R. Hawkins	C. L. Rea, Univ. of Idaho, Moscow, Idaho.
Iowa State College...... Apr. 15, '03	Roscoe Schaffer	F. A. Robbins, Iowa State College, Ames, Iowa.
Iowa, Univ. of......... May 18, '09		A. H. Ford, University of Iowa, Iowa City, Iowa.
Kansas State Agr. Col...Jan. 10, '08	L. V. Fickle	Clarence E. Reid, Kansas State Agric. Col., Manhattan, Kan.
Kansas, Univ. of....... Mar. 18, '08	E. C. Arnold	E. C. Bourke, University of Kansas, Lawrence, Kansas.
Kentucky State, Univ. of Oct. 14, '10	Harry Y. Parker	G. F. Campbell, 345 South Limestone Street, Lexington, Ky.
Lafayette College...... Apr. 5, '12	R. McManigal	W. J. English, Jr., Lafayette College, Easton, Pa.
Lehigh University...... Oct. 15, '02	A. F. Hess	R. W. Wiesman, Lehigh University, South Bethlehem, Pa.
Lewis Institute........ Nov. 8, '07	A. H. Fensholt	F. A. Rogers, Lewis Institute, Chicago, Ill.
Maine, Univ. of........ Dec. 26, '06	H. H. Beverage	W. E. Bowler, Univ. of Maine, Orono, Me.
Michigan, Univ. of..... Mar. 25, '04	H. A. Enos	H. W. Stubbs, University of Michigan, Ann Arbor, Mich.
Missouri, Univ. of...... Jan. 10, '03	K. Atkinson,	E. W. Kellogg, University of Missouri, Columbia, Mo.
Montana State Col..... May 21, '07	John M. Fiske	J. A. Thaler Montana State College, Bozeman, Mont.
Nebraska, Univ. of..... Apr. 10, '08	Olin J. Ferguson	V. L. Hollister, Station A. Lincoln, Nebr.
New Hampshire Col.... Feb. 19, '09		
North Carolina Col. of Agr., and Mech. Arts...... Feb. 11, '10	L. B. Jenkins	E. A. Hester, West Raleigh, N. C.
North Carolina, Univ. of.Oct. 9, '14	P. H. Daggett	J. W. McIver, University of North Carolina, Chapel, Hill N. C.
Ohio Northern Univ.... Feb. 9, '12	R. E. Lowe	W. F. Schott, 426 South Union Street, Ada, Ohio.
Ohio State Univ........ Dec. 20, '02	R. G. Locket	D. A. Dickey, Ohio State University, Columbus, Ohio.
Oklahoma, Agricultural and Mech. Col........... Oct. 13, '11	J. C. Woodson	W. C. Lane, Oklahoma A. and M. College, Stillwater, Okla.
Oklahoma, Univ. of.... Oct. 11, '12	C. K. Karcher	W. Miller Vernor, Univ. of Oklahoma, Norman, Okla.
Oregon, Agr. Col.,...... Mar. 24, '08	W. R. Grasle	Winfield Eckley, Oregon Agric. College, Corvallis, Ore.
Penn State College..... Dec. 20, '02	W. L. Kirk	A. C. Horst, State College, Pa.
Pittsburgh, Univ. of,.... Feb. 26, '14	G. W. Flaccus	Ralph C. Zindel, University of Pittsburgh, Pittsburgh, Pa.
Purdue Univ.,......... Jan. 26, '03	L. W. Spray	R. E. Tafel, Purdue Univ., Lafayette, Ind.
Rensselaer Poly. Inst... Nov. 12, '09	W. J. Williams	S. N. Galvin, Rensselaer Polytechnic Institute, Troy, N. Y.
Rose Polytechnic Inst.,. Nov. 10, '11	Warren F. Turner	F. Edward Bundy, 1103 N. 8th Street, Terre Haute, Ind.
Rhode Island State Col. Mar. 14, '13	Charles E. Seifert	Frank A. Faron, Rhode Island State College, Kingston, R. I.
Stanford Univ.......... Dec. 13, '07	A. B. Stewart	H. J. Rathbun, Stanford University, Cal.
Syracuse Univ.,......... Feb. 24, '05	W. P. Graham	R. A. Porter, Syracuse University, Syracuse, N. Y.
Texas, Univ. of........ Feb. 14, '08	J. M. Bryant	J. A. Correll, Univ. of Texas, Austin, Tex.
Throop College of Technology.............. Oct. 14, '10	R. S. Ferguson	W. M. Holmes, Throop Poly, Institute, Pasadena, Cal.
Virginia Polytechnic Institute................ Jan. 8, '15	M. F. Peake	J. R. Murphy, Virginia Polytechnic Institute, Blacksburg, Va.
Virginia, Univ. of....... Feb. 9, '12	W. S. Rodman	H. Anderson, Jr., 1022 West Main St., Charlottesville, Va.
Wash. State Col. of.... Dec. 13, '07	M. K. Akers	H. V. Carpenter, State Coll. of Wash. Pullman, Wash.
Washington Univ....... Feb. 6, '04	C. C. Hardy	Charles P. Seegar, Washington University, St. Louis, Mo.
Washington, Univ. of Dec. 13, '12	H. W. McRobbie	B. B. Bessesen, Univ. of Washington, Seattle, Wash.
West Virginia Univ. .... Nov. 13, '14	H. C. Schramm	C. L. Walker, West Virginia Univ., Morgantown, W. Va.
Worcester Poly, Inst... Mar. 25, '04	R. M. Thackeray	C. C. Whipple, Worcester Polytechnic Institute, Worcester, Mass.
Yale University........ Oct. 13, '11	Vonder Smith	

Total 52.

SECTION II

PROCEEDINGS

of the

American Institute

of

Electrical Engineers

Papers, Discussions and Reports

CONTENTS OF SECTION II

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md. July 1, 1915.

CONTACT SYSTEM OF THE BUTTE, ANACONDA & PACIFIC RAILWAY

BY J. B. COX

ABSTRACT OF PAPER

A careful study of the general conditions existing on the B. A. & P. R. R. indicated that an overhead contact system was advisable.

The relatively large amount of energy required per locomotive unit made the adoption of the roller pantagraph desirable. The weight of this type of collector demanded that the trolley line be made as flexible as possible.

Special hangers, pulloffs, etc., were designed to accomplish this result. The cost of the contact system was relatively high because of the unusual conditions.

The operation is quite successful, though some minor troubles were experienced in the beginning.

A CAREFUL preliminary survey of the general problems involved in the electrification of the Butte, Anaconda & Pacific Railway had made it evident that an overhead contact system was unquestionably advisable, the two predominating reasons being, that approximately 60 per cent of the tracks to be electrified consisted of yards and sidings, with numerous switches and street crossings, and that a great portion of these tracks were in localities where it would be very difficult to protect against trespass by the public.

An analysis of the general traffic conditions had indicated that a locomotive unit with approximately 80 tons on drivers, and equipped with an aggregate motor capacity of approximately 2400 h.p., for maximum accelerating periods, would be most economical and best suited to the general service conditions, two such units being operated in multiple as a single locomotive for the heavier freight trains. Such a locomotive would thus require to receive at its collectors from the trolley frequently from 3000 to 3600 kilowatts which would mean 6000, 3000 or 2500 amperes at 600, 1200 or 1500 volts respectively.

Trial estimates on total initial costs and final operating ex-

Manuscript of this paper was received June 12, 1915.

penses for the entire electrification had indicated that, for the general conditions, direct-current motors operating two in series from a 2400 volt trolley fed from two substations, one located at each end of the line in existing power supply buildings approximately 26 miles apart where no extra attendants would be required, would be expected to yield most economical results. Higher trolley voltages were considered but were not found to be generally advantageous.

A double-unit locomotive with capacity as described would therefore, require to collect from the 2400-volt trolley during acceleration from 1400 to 1500 amperes or 700 to 750 amperes for each collector, one being used per unit.

While this was known to be well within the capacity of a single 4/0 trolley wire fed at frequent intervals from both directions, the successful collection of such a heavy current from a single trolley wire was a more serious problem.

Sliding pantagraphs of various types had been developed and made to operate fairly successfully for the collection of currents up to 150 to 200 amperes under similar operating conditions but none had given any hopeful indications of collecting such heavy currents with reasonably satisfactory life.

Rollers of various kinds had been tried as substitutes for the slider and one of these, made from steel tubing, had been found to give very satisfactory results, and on the whole, seemed to be the most promising prospect at the time so that this type of collector was chosen for the moving contact device on the locomotives.

A Shelby steel tube 5 inches in diameter and 24 inches long was used for making up the roller. The thickness of this tube when turned up inside and outside was approximately $\frac{1}{8}$ inch. A wooden lining was originally forced inside the tube which was expected to hold the tube together until the sparking had called attention to the necessity for its removal in case it wore through the metal.

Removable bearing housings of aluminum metal were fitted into each end of this tube, two phosphor-bronze sleeve bearings being installed in each housing, between which was an oil chamber for containing the lubricant. The complete roller revolved about a $\frac{5}{8}$-in. steel shaft which was fixed at each end by clamps to the pantagraph frame.

The completed roller with lining, bearings and spindle weighed approximately 31 lb., as against about 5 lb. for the corres-

ponding contact element usually adopted for the sliding pantagraph.

This comparatively heavy contact device could not be expected to respond so readily or so gently to hard or uneven spots in the trolley wire as does the lighter slider. Besides the increase in weight, the rapid revolving of the roller at high speeds would tend to increase the difficulties unless the balance was almost perfect. These difficulties were foreseen from the beginning and as it was realized that the weight of the roller could not be materially reduced it was decided to adopt practically the standard pantagraph frame with such changes as were necessary for the substitution of the roller, and to turn to the trolley line construction with a view to removing the most serious objections to the roller by avoiding the hard or uneven spots in the trolley line, which seemed to be its greatest enemy.

The pantagraph as originally installed on the locomotives is illustrated in Fig. 1. One such pantagraph was put on each freight locomotive unit and two on each passenger unit, though only one pantagraph is used at a time, the extra one being a spare one for use in case of trouble, thus to avoid unnecessary delay. All main line freight trains are operated by a double-unit locomotive with both pantagraphs in contact with the trolley wire and connected in multiple by means of a bus line run on top of the locomotives with a jumper connection between the two units.

In case of accident to either pantagraph on these trains a single pantagraph is capable of collecting the current for both units for the completion of the trip. The operation of this pantagraph in service is detailed further on in this article.

In considering what might be done by way of improving the design of the overhead line construction so as to make it more adaptable to the satisfactory operation of the roller pantagraph evenness and flexibility were the qualities most desired.

The introduction of catenary construction with hangers at frequent intervals had accomplished much in these directions, especially the first, and gradual improvements had been made toward simplifying and cheapening this type of construction, though perhaps the importance of flexibility had not been fully appreciated until the heavier types of collector became desirable.

Attention was directed to the redesigning of all hangers, pull-offs and other of the line material which tended to add unevenly

TABLE I—DIMENSIONS OF HANGERS AND STRUTS CATENARY CONSTRUCTION.

ELEVEN POINT SUSPENSION. TWENTY-EIGHT INCH DEFLECTION.

Degree of curvature	Radius	Pole spacing	No. of hangers	Hanger spacing	No. of pull-offs	Pull-off spacing	Hanger Lengths—(Inches)															Strut Lengths				
							8	8¾	11	13½	14¾	16½	18¾	19½	20½	21¾	23 5/16	24¾	25½	26 3/16	27	14	17	20	23	26
Tangent	Track	150	11	13′ 7 7/11″	0		1	2	2	..	2	..	2	..	..	..	..	2	..	..	..	..	..	..	..	..
1°	5730	150′	11	13′ 7 7/11″	1	150′0″	1	2	2	..	2	..	2	..	..	..	..	2	..	..	..	..	..	..	..	..
2°	2865	150′	11	13′ 7 7/11″	2	55′0″	1	2	2	..	2	..	2	..	..	..	..	2	..	..	..	2	..	..	..	..
3°– 4°	1910–1432	125′	9	13′10 2/3″	2	62′6″	..	..	..	1	2	2	..	2	..	..	..	2	..	..	..	..	2	..	..	..
5°– 6°	1146–955	110′	8	13′ 9″	2	77′0″	..	..	..	..	..	2	2	..	2	..	..	..	2	..	..	..	2	..	..	..
7°– 9°	818–636	95′	7	13′ 6 6/7″	3	31′8″	..	..	..	..	..	..	..	1	2	2	..	..	..	2	..	..	1	..	3	..
10°–12°	573–477	80′	6	13′ 4″	3	26′8″	..	..	..	..	..	..	..	..	..	2	2	..	..	2	..	..	..	1	2	..
13°–15°	441–382	70′	5	14′ 0″	4	17′6″	..	..	..	..	..	..	..	..	..	..	1	2	..	2	..	..	..	..	2	2
16°–20°	358–286	55′	4	13′ 9″	4	13′9″	..	..	..	..	..	..	..	..	..	..	..	..	2	..	2	..	..	..	2	2

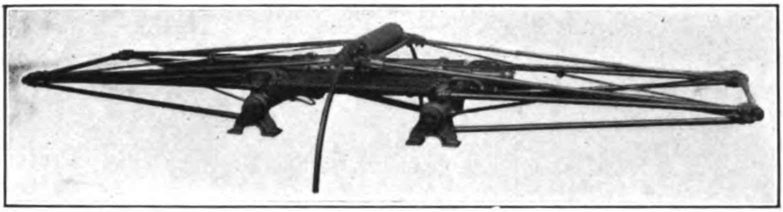

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FIG. 1—PANTAGRAPH TROLLEY

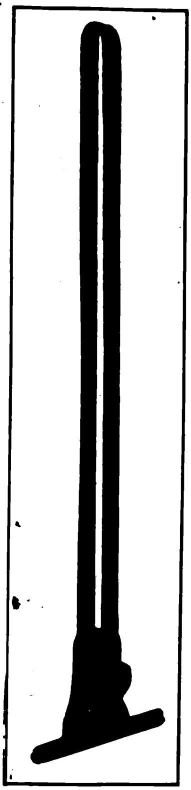

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FIG. 2—FORM C H HANGER

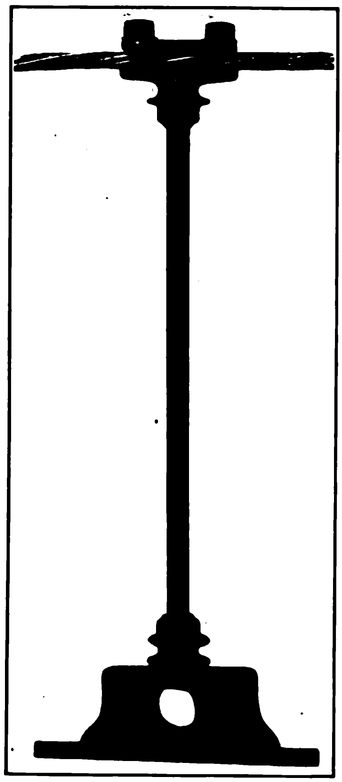

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FIG. 5—RIGID CATENARY PULL-OFF

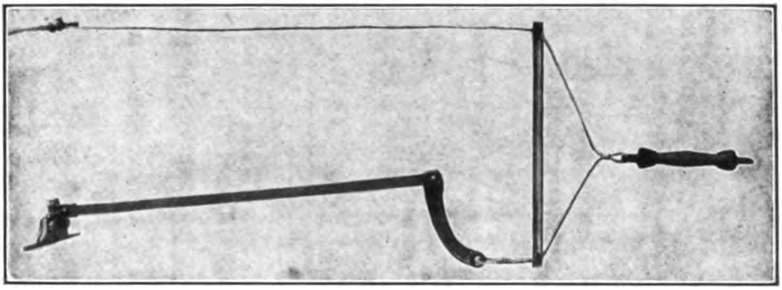

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FIG. 3—FLEXIBLE PULL-OFF FOR PANTAGRAPH COLLECTOR

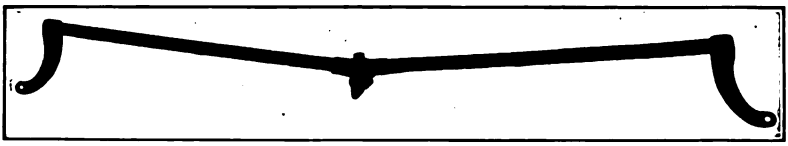

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FIG. 4—DOUBLE FLEXIBLE CATENARY PULL-OFF

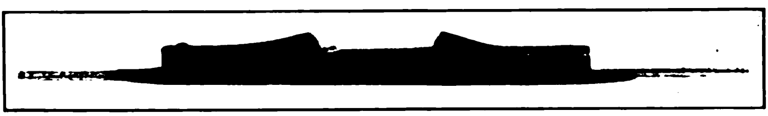

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FIG. 6—SPLICING SLEEVE, WEDGE TYPE, RENEWABLE SHOE, FOR PANTAGRAPH COLLECTOR

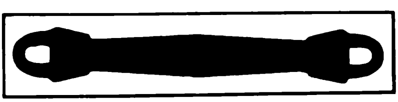

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FIG. 8—FORM A WOOD STRAIN INSULATOR

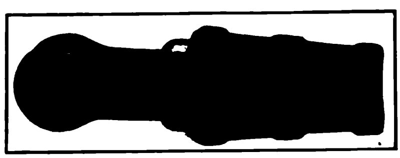

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FIG. 7—WEDGE GRIP CLEVIS

distributed weight or local stiffness to the trolley wire, the result being the development of a new line of this apparatus.

The new hanger was made up of $\frac{5}{8}$ by $\frac{1}{8}$-in. flat strap with a malleable iron ear secured by a $\frac{1}{2}$ by 1 $\frac{1}{2}$-in. carriage bolt. This hanger allows the greatest possible vertical movement of the trolley wire, or more than the upward pressure of the two pantagraphs of a double unit locomotive operating with a tension of 35 to 40 lb. each against the trolley wire will normally raise it, before any resistance from the messenger is encountered, since the loop extends for almost the entire length of the hanger. The hanger is simple in construction and easily installed as the loop is merely thrown over the messenger and the two ears carried by the loop strap are secured by the single bolt which at the same time clamps the self aligning jaws into the grooves of the trolley wire.

The design of the jaws give liberal clearance for the roller and would readily permit the operation of a trolley wheel should such for any reason be desired.

The weight of the complete hanger varied from 14$\frac{1}{2}$ oz. in the case of the 8-in. to 1$\frac{3}{4}$ lb. for the 28-in. or longest. This hanger is shown in Fig. 2.

As a very large percentage of the trackage to be electrified is curve construction, varying any where from tangent to 22 deg., it was necessary to give most careful attention to the design of a new pulloff. The result of the efforts in this direction was an entirely new pulloff, by means of which the messenger and trolley wires are held in position by separate clamps, from each of which run an individual pulloff wire with a strut between, maintaining the pull parallel to the horizontal plane of the trolley wire, allowing free vertical movement independent of the messenger, Fig. 3.

The double pulloff used where there was more than one track is shown in Fig. 4. This pulloff, while an improvement in some respects over former designs, was not as satisfactory as the single pulloff, as it proved to be heavier and less flexible than was desired, causing slight sparking when a single pantagraph passed underneath it at medium speeds.

The design has been revised and future construction will be considerably improved.

Rigid pulloffs as shown in Fig. 5 were used at some points but were found to be subjected to much the same objections as the double pulloffs because of the sparking due to similar reasons.

The type of splicing sleeve used is shown in Fig. 6. It is made of sheet steel with a malleable iron removable shoe which gives a smooth underrun for the roller, and may be replaced when worn out before the body of the holding member proper is injured.

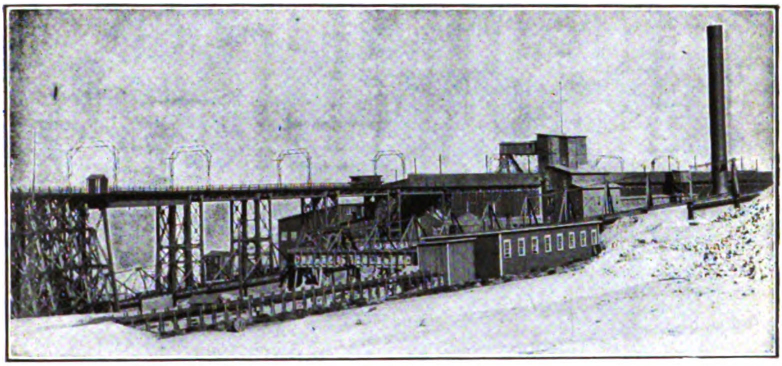
The wire is securely held by a drop forged wedge with sharpened teeth, without bending the wire or diminishing its tensile strength.

Fig. 7 illustrates the form of wedge grip clevis used for dead-ending the trolley and messenger wires. This had double wedges with sharpened teeth similar to those for the splicing sleeve.

These are readily installed with a hammer, which together with their low manufacturing cost and ease of adjustment in service, makes their use economical as well as satisfactory.

The question as to the use of wood or steel poles for the supporting structure was not a difficult one owing to the general conditions and the nearness to the best of markets for good Idaho cedar poles which made their use more economical when compared with the cost of steel structure. Some consideration was given to the use of steel structure in some of the yard construction where as many as eight tracks were to be spanned, but even here it was finally decided to use the wood poles though the general advantages were not so great as on the main line construction. However, steel supporting structures were used on the double track steel trestle running from the concentrator yards up over the ore storage bins alongside the concentrator buildings, Fig. 7A. These tracks are approximately $\frac{1}{2}$ mile in length. The steel supporting structure was made up at the smelter and the cost of same is included in Table II.

A further item of unusual character in connection with the trolley line construction was that required for about $\frac{1}{4}$ mile of track alongside a slump pond from which the sediment is taken by means of a drag line scraper bucket operated from a cableway suspended between two traveling towers mounted on rails on each side of the pond. As the track in question on which empty cars are placed for loading is located inside the area covered by the cableway, a trolley wire over the center of the track would interfere with the loading, and as it was desirable to use a standard locomotive for the handling of these cars, the brackets which supported the trolley and messenger wire were hinged at the pole. A flexible wire cable attached to the outer end and passing over a pulley anchored on top of



[cox]

FIG. 7A—STEEL SUPPORTING STRUCTURES ON TRESTLE

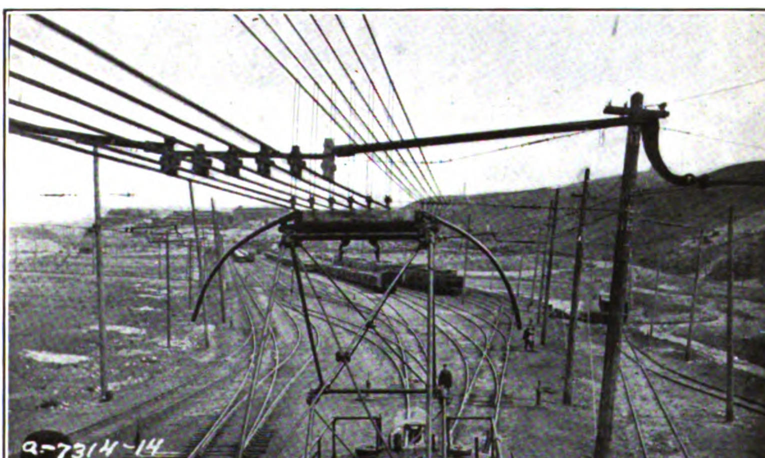


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FIG. 9—SIX TROLLEY WIRES IN SIMULTANEOUS CONTACT WITH ROLLER COLLECTOR

the pole was connected to a hand-operated windlass by which the brackets are swung upward carrying the trolley line from over the track and clear of the path of the bucket. When the loading is completed the trolley is lowered to the normal position while the loaded cars are removed and replaced by other empties. The number of poles and costs will be found in Table III.

TABLE II.—COST OF DISTRIBUTION SYSTEM.

	Cost per item	Cost per mile
Labor installing	$129,027.56	$1417.89
Feeder copper	89,697.00	985.68
Work train service	64,268.31	706.25
Trolley wire	58,213.60	639.71
Cedar poles	27,739.21	304.83
Galvanized strand wire	26,807.47	294.59
Copper bonds	20,564.20	225.98
Hangers	7,596.27	83.48
Crosby clips	5,396.17	59.30
Wood strain insulators	5,385.22	59.18
Engineering and superintendence	5,289.30	58.12
Tools	3,811.30	41.88
Anchor rods	3,403.73	37.40
Sectionalizing switches	3,097.05	34.03
Injuries and damages, etc	3,036.56	33.37
Fitting up work cars	2,292.61	25.19
Steel and iron from stock	2,043.87	22.46
Lumber and timbers	2,013.61	22.13
Rental on work cars	1,716.50	18.86
Shop expenses	1,418.59	15.59
Lightning arresters	1,271.02	13.96
Paints and oils	901.32	9.90
Feeders and messenger insulators	842.15	9.25
Creosote and oil	637.00	7.00
Steel bond protectors	570.00	6.26
Splicing sleeves	294.00	3.23
Postage, car-fares, etc	238.62	2.62
Guards and signs	234.08	2.57
Wedge grips	130.01	1.43
Dynamite and fuses	121.36	1.33
Gasoline, solder, etc	100.46	1.10
Miscellaneous items	33,629.50	369.55
Total	$501,787.74	$5514.15

The question of insulation was not a serious one as trolley voltages up to 11,000 volts had been in operation for a number of years and insulation difficulties for such purposes had been met quite satisfactorily, so that the question was merely a matter of choice between wood and porcelain, the decision eventually being made in favor of wood as the dry climate in the lo-

cality was favorable to its satisfactory service with greater general economy.

The wood strain insulators used are shown in Fig. 8 and the number used and costs are given in Table III.

Insofar as the general plan of trolley construction is concerned no very decidedly radical departures from some of the later installations was attempted but every effort was made to simplify and perfect what has been done before and to adapt the construction to the particular conditions.

A very important item in the way of economizing and simplifying was the omission of the use of any form of deflector at all special work. Some new departures were made in the manner

TABLE III.—SHOWING AMOUNTS AND COSTS OF PRINCIPAL MATERIALS REQUIRED FOR DISTRIBUTION SYSTEM.

	Total units	Units per mile	Costs per unit cents	Total cost
Feeder copper, lbs.	507,055	5,572	17.69	$89,697.00
Trolley copper, lbs.	343,030	3,770	16.97	58,213.60
Cedar poles	4,869	53.5	569.71	27,739.21
Galvanized steel strand, feet	1,553,750	17,074	1.73	26,807.47
Copper bonds	32,260	355	63.74	20,564.20
Crosby clips	61,911	680	8.72	5,396.17
Wood strain insulators	15,850	175	33.97	5,385.22
Anchor rods	6,123	673	55.57	3,403.73
Splicing sleeves	265	3	111.00	294.00
Wedge grips	680	7.5	19.13	130.01
Total	....	....	....	$237,630.61

of arrangement of the trolley wires at these points so as to insure the pantagraphs picking up and dropping them properly.

At switching points in ordinary trolley construction frogs are employed to make the trolley junction, and for pantagraph use deflectors are generally required to prevent the pantagraph when approaching such a junction toward a trailing switch from raising the wire under which it is operating, sufficiently above that over the converging track so as to allow the pantagraph to get over it without destructive results to either the pantagraph or trolley or both. Instead of this construction, the trolley and messenger wires which were intended to follow the switching track was started several feet ahead of the switch from a convenient point for dead-ending, and several inches

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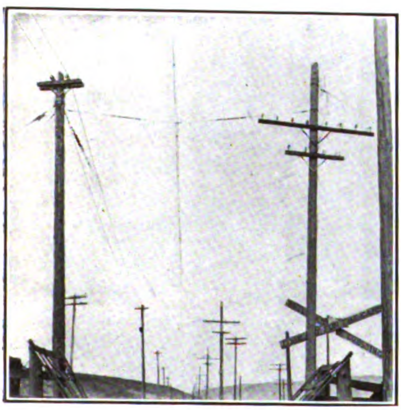
FIG. 10—STOCK BIN YARD—SMELTER HILL



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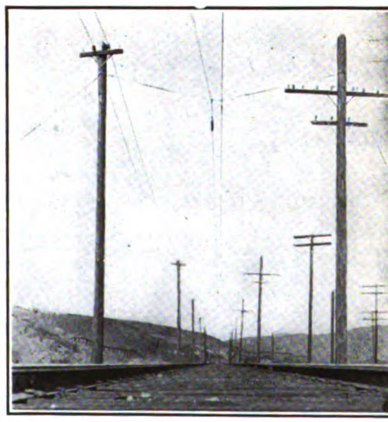

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FIGS. 11 and 11A—AIR SECTION INSULATOR

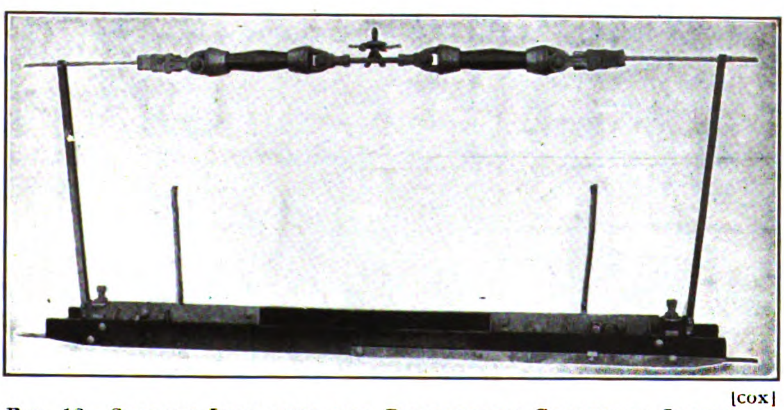

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FIG. 12—SECTION INSULATOR FOR PANTAGRAPH COLLECTOR INSTALLED AT CROSS SPAN

above the horizontal plane of the through wires, and gradually brought down to that plane a short distance ahead of the switching point where they were gradually carried away following over the switching track. At some points in the yards where the parallel tracks leave the ladder track at close intervals as many as six sets of wires are in the same horizontal plane and all the trolley wires making contact with the roller simultaneously, Fig. 9.

This construction has proved entirely satisfactory and there have been no instances of trouble from the omission of deflectors, which not only lessened the cost of the work but avoided much extra weight at points where the supporting structure was most taxed. Fig. 10 illustrates of the above construction.

Air section insulation was used at all points where it was practicable and has been found to be advantageous from every point of view. Instead of inserting wooden insulators in the trolley line where sectionalization was desired, the ends of the wires of each section were made to overlap each other the length of a pole spacing, the two sets of wires being carried in approximately the same horizontal plane but about 12 inches apart for a few feet in the middle of the span, from which point the dead ends of the trolley wire were gradually carried above the path of the collector to its anchorage.

This construction avoids the use of heavy insulators thus preventing hard or heavy spots in the line which are destructive to the line and pantagraph alike. With this construction there is less objection to sub-dividing the line into a number of short sections, which, with the elasticity provided by wood poles and catenary suspension, overcomes to a great extent, the difficulties arising from contraction and expansion due to changes in temperature.

These sections are passed at full speed without any noticable effect on the line or the pantagraph or the least interruption of contact.

Similar construction was used at all anchoring points for both trolley and messenger and has been found to be equally satisfactory here. Undoubtedly this type of sectionalizing will become much more general in the future and means will be devised for its adoption at points where it is now found difficult to install properly.

Tests were made by cutting the current off of one section and running a locomotive from the live section onto the dead sec-

tion at slow speed and heavy current to see if the arcing between the pantagraph and the live trolley wire would be injurious. The arcing was surprisingly small and not of a nature to do serious harm to either wire or roller. Fig. No. 11 shows the general method of installation.

The effect of such an operation in the case of the wooden section insulators used at 600-volt street railway crossings and and other points where it was not found convenient to install the air type was quite injurious, and though such tests were not meant to be given them and the insulators were not expected to stand such treatment repeatedly, some of those, located at street crossings where considerable switching was done, received the test too frequently and sooner or later broke down under the treatment.

At these street railway crossings it was necessary to use two such insulators in the 2400-volt line about 75 feet apart, the trolley section in between being called the protecting zone, this being made necessary on account of the operation of double-unit locomotives with a trolley on each up, and the two being connected by a bus line.

As the first insulator was usually about 100 ft. from the switch and the safety section was not energized until a member of the train crew ran ahead and threw a commutating switch located on a pole near the street crossing which cut off the commutating section from the normal 600-volt connection and energized it with the 2400-volt current so long as the switch handle was held in the full up position, it frequently happened in the earlier period of electrical operation, before the crews had learned from actual experience the damage that might result, that the member of the crew whose duty it was to run ahead and operate the switch did not get it thrown until the locomotive had passed under the first insulator, and as this was often done with power on the motors, the arcing that occurred when the roller left the live section of the insulator and ran onto the dead section carbonized the wood of the insulator and the carbonization was extended with each repetition until the insulation was finally insufficient and the insulator had to be replaced. The insulator originally used at these points is shown in Fig. 12. These experiences suggested the advisability of a change in the design of the insulator which would render the arcing in such instances less destructive, so that the overlapping metal contact strips which originally were attached

directly to the bottom of the wood insulators, were replaced by other strips which were carried out about four inches away from the wood insulation, thus making the distance between the strips considerably greater. These strips were attached to the insulators by spring hinges, so as to lessen the blow to both the insulator and pantagraph. These insulators were quite an improvement over the original ones but even they were not entirely free from injury when heavy currents were broken under the conditions heretofore described.

The B. A. & P. tracks cross local 600-volt street railway tracks at six points, four of which are at street level in Butte. Two are at the Anaconda end but these, not being at street crossings, avoided the use of the special switching devices by arranging with the street railway company to coast over the crossing. At two of the crossings in Butte watchmen were permanently employed to operate gates for protecting the traffic. The electrical switches for controlling the crossing at these points were placed on poles near the watchman's tower where he could easily operate them, and were interlocked with the gates so as to make it impossible to energize the crossing with the 2400-volt current until the gates were closed or to open the gates while the switch was in the 2400-volt position.

Practically no trouble was experienced at these points after the watchmen became accustomed to their new duties but at the less frequently used crossings where the train crews operate the commutating switches, some troubles were experienced with the switches in addition to that already noted with the section insulators. These switches were not expected to open heavy currents but the operators were expected to hold them in until the locomotive had entirely cleared the protecting zone, but occasionally this was not done, or, to aggravate matters, the switch was allowed to open only partly while the locomotive was still in the protecting zone and when arcing was noticed in the switch box the handle was dropped and the switch badly burned. These commutating switches are shown in Fig. 14. At one point where this trouble occurred a second time, electrically operated contactors were placed in series with the ordinary operating switch on both the 2400-volt and the 600-volt circuit, and two sets of contactors being so interlocked as to render it impossible for the two sets to be energized at the same time, as shown in Fig. 15.

No further troubles were experienced from this cause after

the installation of the contactors. These switches have been redesigned for future installations. After the men had become familiar with the operation of the switches there were very few instances of trouble even with the original switches.

The trolley line was sectionalized at intervals as shown in Fig. 16, which also shows the final feeder arrangement. The sectionalizing switches were placed in asbestos lined wooden boxes and located on trolley poles well out of reach from the ground. An operating lever was located at a convenient point on the pole and at a suitable distance from the ground for ease in handling, and is provided with a standard track switch padlock so that no extra key is required by trainmen for its opera-

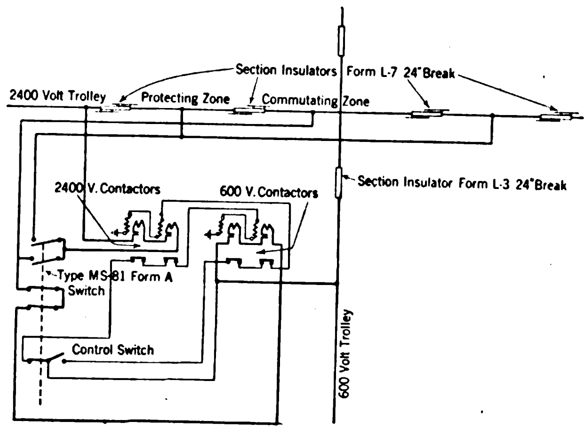

FIG. 15—DIAGRAM OF CONNECTIONS AT 600 VOLT STREET RAILWAY CROSSING SHOWING COMMUTATING ARRANGEMENT AND PROTECTION FROM 2400-VOLT SYSTEM WITH ELECTRICALLY-OPERATED CONTACTORS IN SERIES WITH REGULAR COMMUTATING SWITCH

tion. The operating handle is connected with the switch blade by a wooden rod which provided adequate insulation.

In addition to the sectionalizing of the main line, these switches were used at all yards and at most spurs and transfer tracks to connecting lines, and at such of these points when the service was infrequent, the switch was normally left open. Such transfer connections were made with four other railway lines viz: Great Northern, Northern Pacific, Chicago, Milwaukee & St. Paul, and the Oregon Short Line.

Eleven-point suspension with 28-inch deflection was used throughout with pole spacing, hanger length and pulloff arrangement approximately as per Table II.

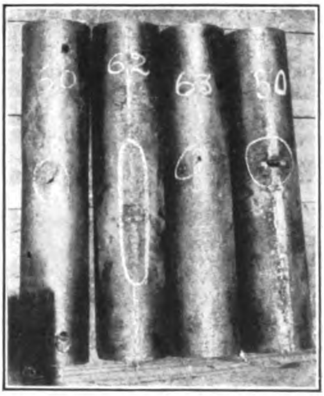

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FIG 13—ROLLER TUBES INJURED FROM SLIDING

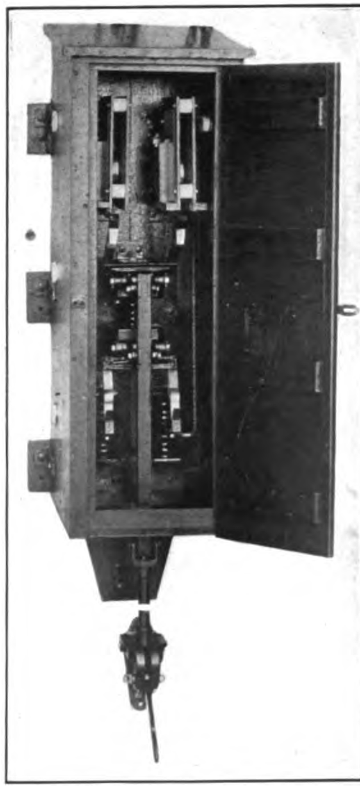

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FIG. 14—COMMUTATING SWITCH, COVER OPEN

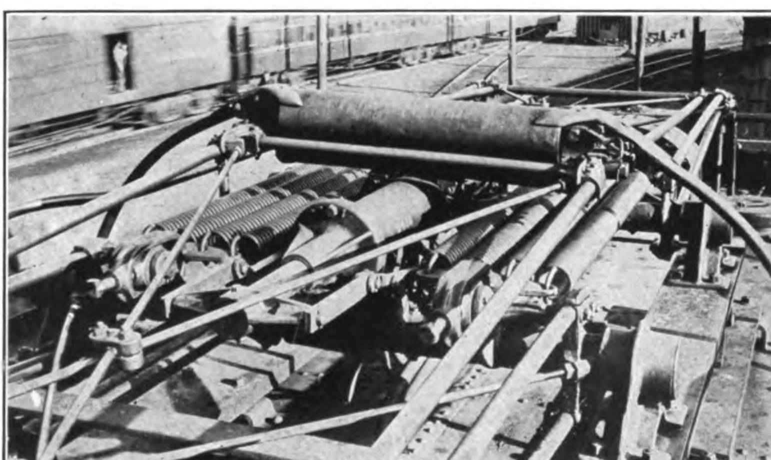

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FIG. 21—REVISED WEARING PLATE FOR ROLLER PANTAGRAPH

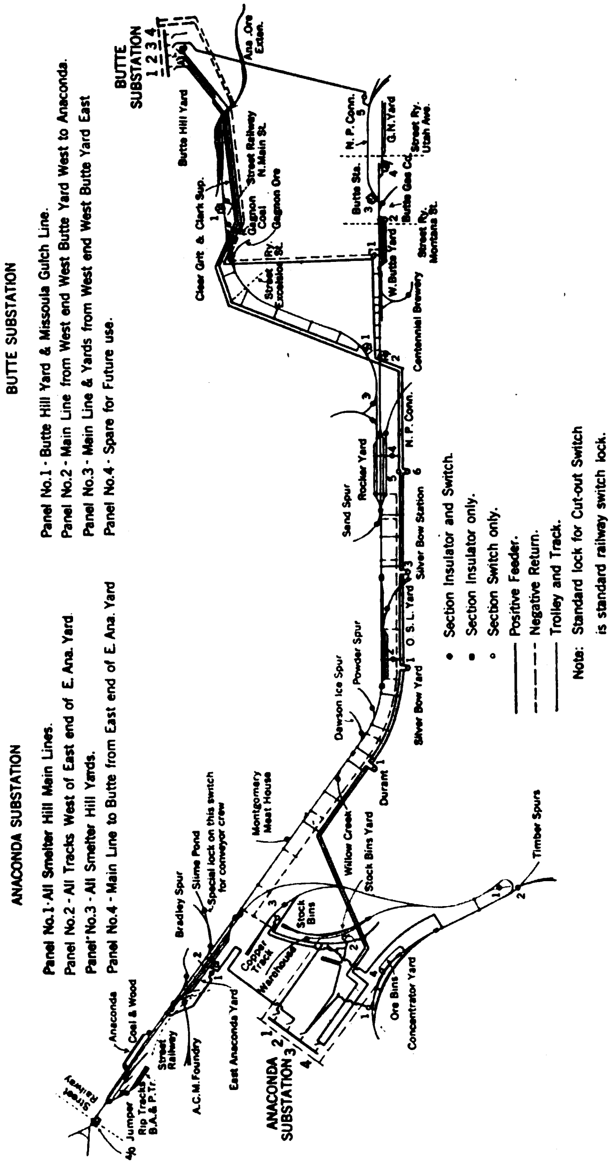


FIG. 16—SECTIONALIZATION OF TROLLEY LINE AND FEEDER SYSTEM

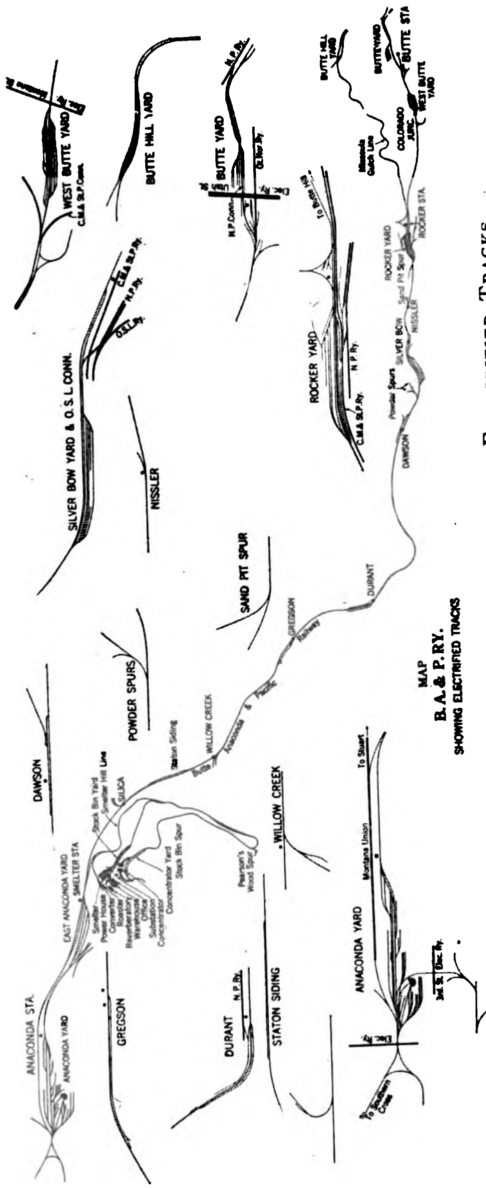


FIG. 17—MAP OF B. A. & P. RY. SHOWING ELECTRIFIED TRACKS

Approximately 10 per cent of the 91 miles of track electrified was bracket construction, which was used on nearly all tangent single track. These stretches of tangent track were so short comparatively and the percentage and degree of curvature so great, that it was unnecessary to make any speciai provision for staggering the trolley wire. Approximately 38 of the 91 track miles would be classified as route miles, leaving about 53 miles, or roughly 58 per cent of yards, sidings, spurs, etc. These 53 miles were made up principally of eight yards located at Anaconda, East Anaconda, Silver Bow, Rocker, West Butte and Butte on the main line and the Concentrator Bins, Storage Bins, and Butte Hill Yards on branch lines. Fig. 17 shows a map of the relative location of these yards and spurs, as well as the number and arrangement of the tracks, etc.

The East Anaconda yards contained 12 tracks inclusive of

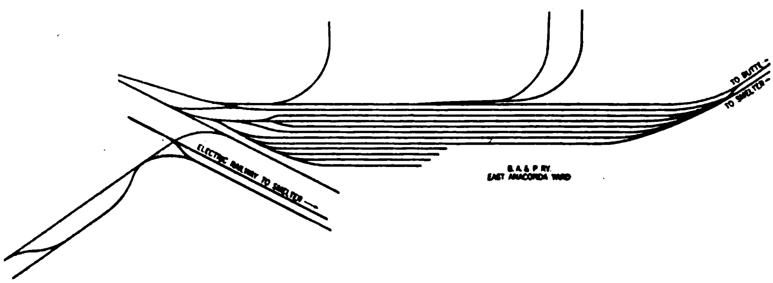


FIG. 18—EAST ANACONDA YARD B. A. & P. RY.

that for the main line, approximating about five miles aggregate trackage, being the largest yard on the system, a plan of which is shown in Fig. 18. Eight of these tracks run almost the entire length of the yard which is approximately one-half mile in length. These eight tracks are spanned by double messenger span wires supported from a pole line on each side spaced approximately 110 ft. apart. The details of this construction with dimensions are given in Fig. 19.

At the western end of the yard there were four additional stub end tracks where a third pole line was erected to form the outside support for the wiring of same.

This eight track span construction has stood up well and is quite satisfactory. All the construction in the yards and spurs were of the standard catenary type and entire freedom from any kind of trouble with it would seem to fully justify any additional expense that such may have required.

The construction work was practically completed in October 1913, though some small extensions were made on Butte Hill in 1914 and are included herein.

Fig. 20 illustrates the form of weekly report that was made to indicate the progress and general condition of the work during construction. As this was the last such report made it represents practically the completed construction and indicates how nearly the original estimates correspond with the final results besides giving many other details of useful interest relative to the nature of the work.

This report was not intended to cover other than the regular construction and, therefore, does not include the entire list of all the items mentioned, and as heretofore mentioned, some further short extensions were made at a later date.

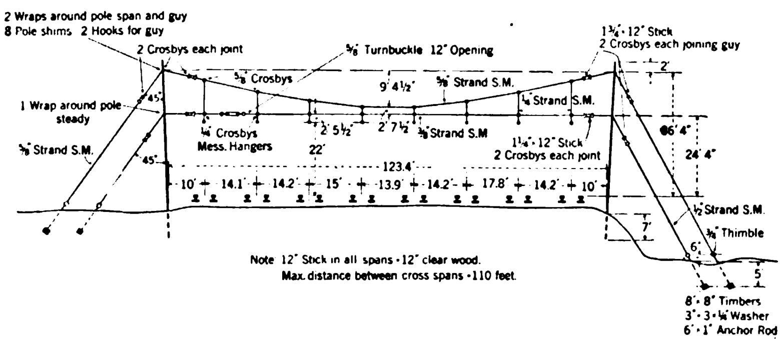
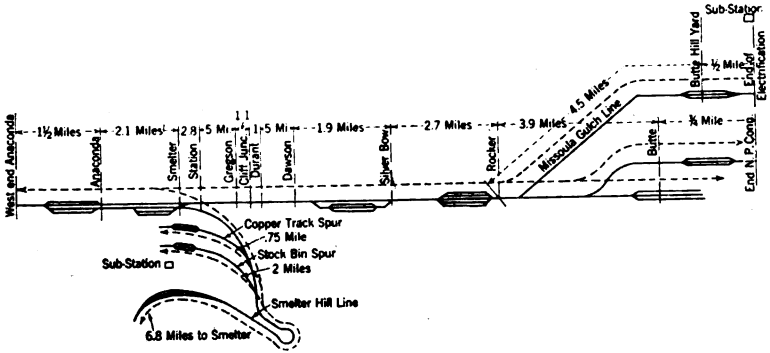


FIG. 19—DIMENSIONS OF CROSS CATENARY SPAN CONSTRUCTION EIGHT TRACKS, B. A. & P. RY.

The total cost of the trolley and feeder system inclusive of bonding and all changes made necessary in the way of clearance for poles, wiring, etc., such as relocation of tracks, telephone, telegraph and light wires, etc., up to the fiscal period ending June 30th, 1914, as reported to the Interstate Commerce Commission, was $501,787.74. This would make the average cost of the overhead system including feeders and bonding per track mile $5,514.15 or per route mile $13,381.00.

An itemized list of these costs is given in Table III, while the amounts and unit costs of the principal items involved will also be found in Table III. The total costs given are from the official records of the Railway Company which are classified in accordance with Interstate Commerce Commission regulations



Remarks:

Great Northern work held up on account of moving freight house.

Construction work finished except:
Wiring of Great Northern Yard at Butte.
Foundry tracks at Anaconda,
Installing new lightning arresters,
Installing signals at railway crossings.

PROGRESS REPORT FOR WEEK ENDING OCTOBER 25, 1913

	Poles	Pole bracket	Cross arms	Pole anchors		Positive feeder	Negative feeder		Trolley and messenger		Spans	Back	Bonds						
				Earth	Rock	600 M. and 500 M.	600M	4/0	Run out	built		Bone	10″	36″	48″	Cross Bond	Long at Frog	Rock	Pole
						miles	miles	miles	miles	miles									Guys
Estimated total for work.........	4250	370	1600	4600	300	55	2	20	54	94	1700	miles	7800	2450	22800	450	300	Holes	7038
Total previously installed........	4846	270	1408	5503	187	51.05	0.89	19.18	98.56	98.56	2580	32.21	7927	2408	19893	175	362	513	19
Installed during current week.....											4								
Total installed to date...........	4846	270	1408	5503	187	51.05	0.89	19.18	98.56	98.56	2584	32.21	79.27	2408	19893	175	362	513	7057

FIG. 20—PROGRESS REPORT

as appears in Table IV, which include the entire cost of the electrification.

The whole of accounts No's, 12, 16, 19 and 22 and such portion of No. 1 as was directly in connection with the distribution system is taken as the total cost of that system.

The listed items in Table No. 2 are approximately correct though in some instances there was some question as to a proper allocation. However, the general results are as nearly correct as is practicable, and even the slightest variations in local conditions would easily offset any likely discrepancy in the proportioning of these costs. The sum of the listed items was subtracted from the total cost and the remainder listed as miscellaneous thereby covering all items of materials and labor,

TABLE IV—COSTS OF THE ELECTRIFICATION OF THE BUTTE, ANACONDA & PACIFIC RAILWAY CLASSIFIED IN ACCORDANCE WITH INTERSTATE COMMERCE REGULATIONS.

Account No.	1. Engineering and superintendence (including general preliminary report)	$10,937.15
" "	12. Roadway tools (used for construction 19 & 22)	3,851.74
" "	16. Crossings, fences, guards and signs mostly for signs	234.08
" "	17. Interlocking and signal apparatus, new system required account of electrification	22,367.62
" "	19. Poles and fixtures (approximately 91 miles track)	135,263.98
" "	22. Distribution system—(approx. 91 miles track wired)	357,009.45
" "	25. Substation building—(existing building used)	191.15
" "	31. 36. } Electrical Equipment—(5, 1000 kw. motor generator sets and 17 locomotive units)	671,764.78
" "	41. Interest	9,975.80
	Total	$1,211,595.75

etc., not definitely specified, leaving no question as to the total cost.

All this construction was done while the road was under full operation and under many conditions which tended to increase the cost above the normal.

The principal items tending to increase the cost were the large percentage of curves and special work, high price of all labor, interference of foreign wire, changes in location of tracks, walkways, platforms, buildings, trestles, bridges, etc., necessary on account of the electrification, extra heavy traffic on the main line, due to the use of fifteen miles of same by a transcontinental line for all traffic while a connecting link for this section was being built, strike of electrical wiremen, cold weather, varia-

tion of ground condition, number of street railway crossings, etc., etc.

It is not likely that the average steam road would encounter so many obstacles of this nature in undertaking the electrification of its lines, for seldom would there be found more complications than in this case where the nature of the work being required for a mining and smelting industry of such magnitude calls for many varieties of structures and conditions not usually to be encountered in ordinary railway electrifications.

The work was begun in the summer of 1912 and was just reaching a state of efficient organization when the electrical wiremen went on strike tieing up the entire work from June to October, about three months of the most favorable part of the year for such work thus bringing the heavy part of the work in the middle of the winter when the weather at times was 20 degrees below zero. During the three months cessation of work the engineering and supervision force was continued at a very low percentage of efficiency and this delay contributed in various other ways to an increase in the cost of the construction.

Some of the items of expense in connection with changes made in existing construction and charged against the distribution system, are approximately as follows:

New telephone line on trolley line poles	$7,850.64
Changing light, power, telephone & telegraph lines	4,273.15
Changing street railway crossings	1,546.65
Relocating railway tracks	815.90
Raising drip sheds	785.54
Changing station platforms	693.29
Raising wagon bridges	361.52
Total	$16,326.69

The new telephone lines in the foregoing list were run on the trolley line poles and were for the purpose of enabling the train crews to communicate with the dispatcher from any locomotive on all of which telephone instruments were installed together with a standard rod for making electrical connections with the wires at any point along the line.

The above list is by no means complete though it gives an indication of the various items represented in the total costs of the system.

Combining eleven pay rolls gives the following classification of labor:

	Days	Avge. Approx. per day	Total
Blacksmiths and helper	27	3.08	$110.58
Boilermakers " "	26	3.76	97.78
Carpenters " "	17	4.40	75.56
Machinists " "	15	4.33	64.91
Electricians " "	3,580	5.71	20,544.09
Pipefitters " "	2	3.80	7.69
Laborers	3,035	3.56	28,611.53
Teamsters	35	3.25	106.96
Electrical foreman	835	6.35	5,300.62
Foremen	665	6.06	4,030.82
Clerks	500	3.35	1,670.42
Totals	13,737	$4.41	$60,620.96

These eleven payrolls represent the principal items of labor in connection with the erection of the trolley and feeder wires, being that for the regular forces engaged in this work and charged against account No. 22, Table IV.

Time and a half was allowed for all overtime and double time for Sunday work in the case of electrical workers.

Wages and perhaps most materials are somewhat higher in this locality than in any to the east of it or than in most any other of the western states.

The operation of the overhead system as a whole has been quite satisfactory in every respect for there have been practically no troubles with it or delays to traffic on account of it. There were two instances of wires slipping in the splicing sleeves due to the wedges not being properly driven up. One of these instances was in connection with the trolley wire and the other with the messenger. In both cases the results were negligible as in the first the trolley hangers slid back along the messenger much as the rings hanging a curtain slide along the supporting wire until the tension was all out, the trolley being held clear of the ground by the messenger; while in the second instance the messenger slid back through the loop of the hanger until the tension was relieved but was supported clear of the ground by the trolley wire, no harm resulting. All that was necessary to remedy the trouble in either instance was to pull the parted wire back into position and properly wedge it into the sleeves. There have been two instances of the trolley wire parting due to improper welding of the metal in manufacture and other similarly negligible instances common to such installations.

TABLE V.—COST OF MAINTENANCE OF DISTRIBUTION SYSTEM OCT. 1913 to MARCH 1915 INCLUSIVE

	Poles and fixtures		Trolley		Feeders		Bonding		Miscellaneous		Total		Total
	Labor	Material	Labor	Material	Labor	Material	Labor	Material	Labor	Material	Labor	Material	Labor and material
Oct. 1913	..	..	..	..	..	..	..	..	291.85	7.50	291.85	7.50	299.35
Nov. 1913	..	..	..	..	..	..	..	..	431.20	264.47	431.20	264.47	695.67
Dec. 1913	..	..	..	..	..	..	..	..	426.35	114.74	426.35	114.74	541.09
Jan. 1914	..	..	..	..	..	..	60.50	..	390.30	88.72	450.80	88.72	539.52
Feb. 1914	..	..	..	..	334.65	..	65.95	..	286.25	784.21	686.85	784.21	1471.06
Mar. 1914	..	..	..	..	32.40	..	64.95	..	570.55	808.51	667.90	808.51	1476.41
Apr. 1914	..	..	..	..	.00	..	37.65	..	313.65	348.95	351.30	348.95	701.25
May 1914	..	..	..	..	00	..	40.20	..	526.75	628.36	566.95	628.36	1195.31
June 1914	..	..	..	..	00	..	24.00	..	473.65	972.08	497.65	972.08	1469.73
July 1914	599.95	14.43	449.25	..	150.95	Cr. 235.64	104.65	..	..	..	1304.80	Cr. 221.21	1082.59
Aug. 1914	219.65	15.09	446.50	..	23.15	320.57	47.40	..	..	..	736.70	335.66	1072.36
Sept. 1914	251.50	26.98	98.70	9.32	00	206.25	24.05	66.22	..	..	374.35	308.77	683.12
Oct. 1914	172.10	00	389.15	.00	26.95	55.86	10.90	00	..	367.94	599.10	423.80	1022.90
Nov. 1914	105.10	.13	165.30	.00	70.90	4.64	43.10	64.57	..	..	384.40	69.34	453.74
Dec. 1914	134.90	6.12	103.45	.48	9.20	42.96	30.85	94.54	..	..	278.40	144.10	422.50
Jan. 1915	115.55	.00	186.95	19.36	49.10	00	94.90	99.68	..	..	446.50	119.04	565.54
Feb. 1915	152.95	2.47	135.15	3.08	63.45	45.41	39.20	97.55	..	..	390.75	218.51	609.26
Mar. 1915	163.55	6.58	141.15	.50	67.05	91.04	58.40	66.02	..	..	430.15	164.14	594.29
Total 18-months	$1915.35	$71.80	$2115.60	$32.74	$827.80	$601.09	$746.70	$488.58	$3710.55	$4385.48	$9316.00	$5579.69	$14895.69
Rate per year	1276.90	47.86	1410.40	21.83	551.87	400.72	497.80	325.72	2473.70	2923.65	6210.69	3719.79	9930.46
Rate per mile per year	14.03	.48	15.50	.22	6.06	4.40	5.47	3.58	27.18	32.13	68.25	40.88	109.13

The most serious interruption that occurred was originated by the blasting out of some old bridge piles by the section men of a paralleling railway. A fragment of the pile was blown against a telephone wire carrying it across the 2400-volt trolley. This telephone wire ran through the switching boards in all the stations along the line, some of which had not then been provided with the proper protecting devices. The result was that the arc set fire to some of the boards, and in one where the operator happened to be temporarily absent at the moment, the building was burned, setting fire to adjacent poles and parting both the trolley and messenger wires.

At the other stations involved where the operators were present and could give prompt attention to putting out the arc started, no serious damage resulted.

The maintenance men who took charge of the trolley system were put on October 1, 1913, consisting of a foreman and two linemen who could requisition other assistance when occasion demanded. The cost of maintenance from this date up to and including March 31st, 1915, covering the first 18 months operation is given in Table V.

Beginning with July, 1914, these accounts were kept more in detail. These expenses include some rearrangements of feeder, etc., and the cost of some special instruments for bond testing and tools. The average cost of the maintenance of the distribution, system inclusive of the track bonding for the 18 months, has been at the rate of $109.13 per track mile per year.

Taking the last nine months during which the costs were segregated more completely gives the following results:

	Poles and fixtures	Trolley	Feeder	Bonding	Misc.	Total
Labor	$1915.35	$2115.60	$460.75	$453.45		4945.15
Material	71.80	32.74	601.09	488.58	367.94	1562.15
Total	$1987.15	2148.34	1061.84	942.03	367.94	$6507.30
Rate per year	2649.53	2864.45	1415.79	1256.04	490.59	8676.40
Rate per year per mile of track	29.12	31.48	15.55	13.80	5.39	95.34
Per cent labor	96	98	43	48		76
" material	4	2	57	52	100	24
" of total	31	33	16	15	5	100

To ascertain the rate of wear on the trolley wire, measurements were recently made on the Smelter Hill line where the traffic is heavier than at any other point and where the electric service has been in operation longest, or just about two years.

The original diameter of the wire vertically was supposed to average about 0.482 inch. The minimum diameter found where the measurements were carefully made was 0.470 inch. The average of a number of measurements was 0.475 inch. It is usually considered safe to allow a 4/0 trolley wire to wear down to 0.350 inch thus allowing a wear of 0.132 inch. If the maximum wear of 0.012 inch as found for the two years is taken as the average during the useful life of the wire, which is at the rate of 0.006 inch per year, the wire can be expected to last 22 years. At this portion of the line there has been an average of approximately 50 passages of pantagraph rollers per day which for two years would be an aggregate of 36,500 passages or 18,250 per year indicating 3041 passages per thousandth of an inch wear.

It is perhaps questionable as to whether the first few months wear on the trolley wire would be at the same rate as after the contact surface had become greater. The outside surface of the wire might be slightly harder than the interior and thus the wear be less at the beginning, while on the other hand when the wire is new the contact area with the roller is quite small and the pressure per unit area together with the increased current density might cause more rapid wear. From such data as is at hand it would appear that the rate of wear on the trolley is greater at the beginning and decreases as the contact area is increased. Extensive tests with a sliding contact, where the operating conditions were varied as to the amount of tension against the trolley wire and current collected, almost invariably indicated that the rate of wear decreased as the area of contact increased, and there seems no reason to suppose that the same would not be true in the case of the roller collector, so that the average life of the trolley wire in this service should not be less than 20 to 25 years.

The roller collectors adopted for the service and described in the beginning of this article have performed their work in general equally as well as had been expected of them, though at the beginning of the electrical operation a number of minor improvements were found desirable. The rollers were operated against the trolley with an upward pressure of approximately 35 lb., the practise being not to readjust so long as the tension was not above 38 or below 33 lb., at the average operating height.

The first difficulties experienced with these rollers was from the sticking of the roller in the bearing, which resulted in their sliding along the trolley wire causing a flat spot or groove which rendered the roller unfit for further service, if not detected at an early stage.

This sticking was first due to the imperfect alignment of the clamping jaws which held the ends of the spindle passing through the roller and on which the bushings revolved. As the bearings consisted of four bushings $1\frac{1}{2}$ in. long, being arranged in pairs, one at each end with a space of one inch between the two bushings of each pair, thus making each bushing substantially four inches in length, it was possible to clamp the ends of the spindle so tightly as to spring it out of line and cause it to bind in the bushings until it did not revolve with the ordinary friction offered by its contact with the trolley wire. This trouble was overcome by more care in the adjustment of the clamps. A little later the caps in the bearing heads began to loosen until they bound the roller between the clamps and caused them to slide as before. A set screw was provided which prevented the unscrewing of the caps and no more trouble from the sliding of the roller was experienced until extremely cold weather came and heavy frost accumulated on the trolley wire which, on being knocked off by the roller lodged on top of the 2 $\frac{1}{2}$-inch " T "-iron brace or hooker frame support underneath the roller with about 1/16 inch clearance, where it piled up and finally clogged the roller causing the sliding of same with results as heretofore.

This difficulty was met by increasing the clearance of both the brace and the roller and inverting the "T" so that the web was on the bottom and thus did not offer so large an area for the collection of the frost. Fig. 13 shows the results of the roller sliding from any cause.

Another defect that threatened trouble at an early stage was the removable cast iron wearing plates screwed on to the pantagraph head at each end of the roller and intended to guide the trolley wire smoothly from the horn onto the roller.

It was found quite difficult to keep this plate in proper alignment with the roller owing to the wearing down of the bushings and the increase in the end play of the roller which allowed the trolley wire to hang in the gap between the wearing plate and the end of the roller, and when this condition was not remedied promptly a groove was soon worn at this point which often made the replacement of the plate necessary and sometimes that of

the roller tube as well. This difficulty was removed by the application of a new type of wearing plate which extended out slightly over the roller with a prong on either side gradually dropping below the line of the top of the roller so that the wire passed from one to the other so gradually that there was no point where the wire was inclined to catch. The lower end of this wearing plate extended out over the upper end of the horn in a similar manner and avoided the necessity of such careful fitting as had been required with the old type where butt joints were used. The new wearing plate is shown in Fig. 21.

The sleeve bearings with oil lubrication were fairly satisfactory in the freight service where the average speed was from 15 to 30 mi. per hr. but when the passenger service was started requiring a schedule speed of 26 mi. per hr. with maximum speeds of 45 to 50 mi. per hr. the bushings wore out very quickly, which allowed the oil to be carried out along the spindle and thrown off, falling on the roofs of the locomotive and the cars, making it necessary to replenish the oil at the beginning of each trip.

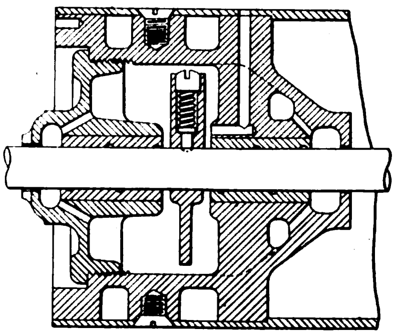


FIG. 22—ORIGINAL ROLLER DESIGNED FOR USE OF SLEEVE BEARINGS WITH OIL LUBRICATION

When the bushings become worn the roller vibrated considerably causing more sparking at the contact with the trolley wire and often breaking the truss rods used for bracing the pantagraph frame. In some instances these bushings were badly worn before they had made 200 miles.

Experiments were made with grease lubrication which gave promise of good results and which led to some slight modification of the bearings and to a general substitution of grease for oil as a lubricant. Fig. 22 illustrates the original bearings.

In the meantime tests were being made with a special roller bearings and the results had been so encouraging that it was decided to substitute these for the sleeve bearings in all the rollers as the latter wore out and required to be renewed. Fig. 23 illustrates the adaptation of the roller bearings to the original bearing housings, and Fig. 24 shows their installation in the later rollers designed for this purpose.

The total locomotive miles made by the electric locomotives up to the end of March 1915, was 927,234. The number of roller tubes received by the railway company up to that date was 123 including those that came on the locomotives and extra pantagraphs, bought for spare parts.

On this date the roller tube stock was as follows:

	5	New rollers complete in pantagraphs.
	29	New tubes in stock.
	20	Partially used tubes on locomotives.
	10	Partially used tubes in stock.
Total	64	Tubes used and unused, 34 of which are new and 30 partially worn, leaving 59 tubes that have been replaced.

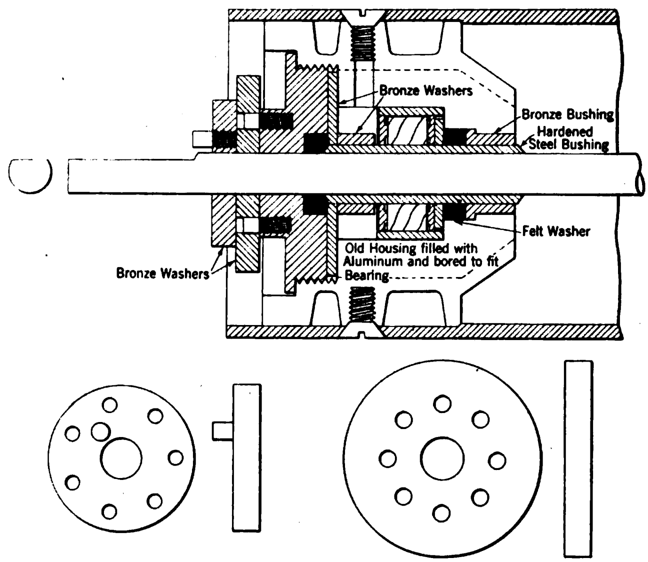


FIG. 23—ORIGINAL HOUSING MODIFIED AND FITTED WITH ROLLER BEARING

The master mechanic estimates that the 30 partially used tubes are on an average about half worn out, on which basis the average miles per roller would be $\frac{927,234}{79} = 11,750$, or supposing that these tubes were two thirds worn out, the average mileage per tube would be $\frac{927,234}{84} = 11,030$ miles.

In this connection it should be noted that eleven of the 59 abandoned tubes were removed before they had been in service

many miles on account of the rollers sticking and sliding along the trolley until a groove was cut in them, as shown in Fig. 13. Some of these tubes were thus injured during the commencement of electrical operations before the defects had all been remedied but most of them were caused by the frost freezing the roller to the T-iron brace underneath, mentioned elsewhere.

A large percentage of the above mileage was made before all the sleeve bearings were replaced by roller bearings or the clearance of the roller above the T-iron had been increased.

Comparatively few rollers that were fitted with the roller bearings when new, have yet had to be replaced, one such, which had been in the passenger service where the average current collected is not so great as in the case of the freight service, though the speed is considerably higher, made 26,880 miles before it was

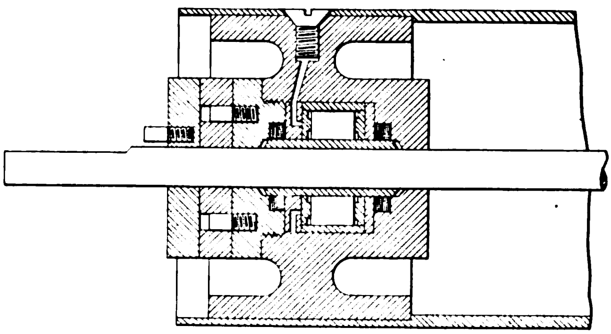


Fig. 24—New Bearing Housing as Fitted in Old Tube by Railway Company

replaced and the average mileage of all tubes with roller bearings at the present time is approximately 16,000 miles indicating that the roller bearings are responsible for an increase of about 35 per cent in the average life of the rollers.

The old sleeve bearings with grease lubrication had to be renewed about each 5000 to 6000 miles, thus requiring about two sets of bushings during the life of a tube. The roller bearings after making 26,880 miles were in perfect condition and it is difficult to judge what mileage they will make, but from present indications it is reasonable to expect that they will make at least 100,000 miles per set. It costs approximately $2.92 in labor and material to renew a set of the old bushings.

The cost of substituting the roller bearings for the bushings was approximately $2.20 for material and $2.25 for labor or

$4.45 per roller. It will thus be apparent that the change was even more important from the point of saving in maintenance of bearings than from increased life of the rollers. The roller bearings require comparatively little attention, a small quantity of fresh grease being inserted at each regular inspection of the engine.

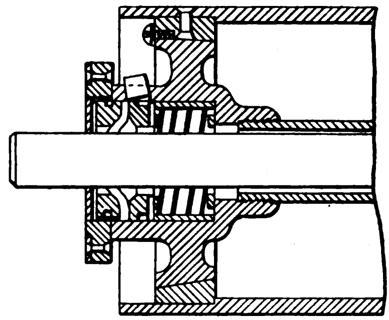


Fig. 25—Latest Type of Roller Specially Designed for Use with Roller Bearing

The general repairs to the entire pantagraph have been likewise affected as the decreased vibration has stopped almost all pantagraph troubles.

The repairs to other parts of the pantagraph during the past six months just passed consisted of renewing six wearing plates, the replacing of two horns and one cross bar. The average cost of maintenance of the original pantagraphs with the sleeve bearings was about $185.00 per month or approximately $3.20 per 1000 locomotive miles. The present corresponding cost of this maintenance is about $35.00 per month or 62 cents per 1000

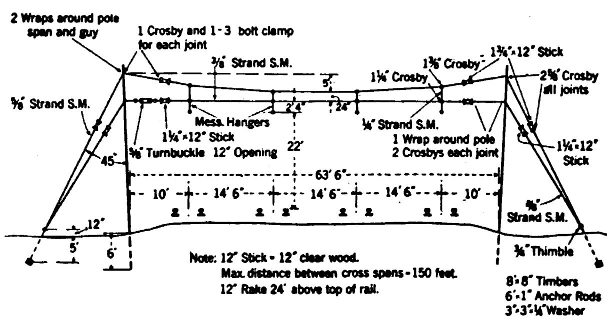


Fig. 26—Dimensions of Cross Catenary Span Construction, Four Tracks, B. A. & P. Ry.

miles, showing a decrease of approximately 81 per cent in this item.

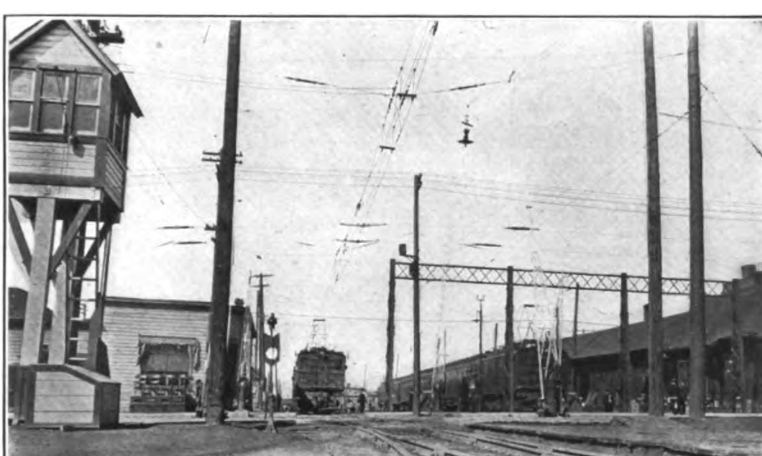
It was found in practise that the wooden lining originally pressed inside the tube was unnecessary and this was left out when the new bearings were installed.

[COX]

FIG. 27—CONCENTRATOR YARD—SMELTER HILL

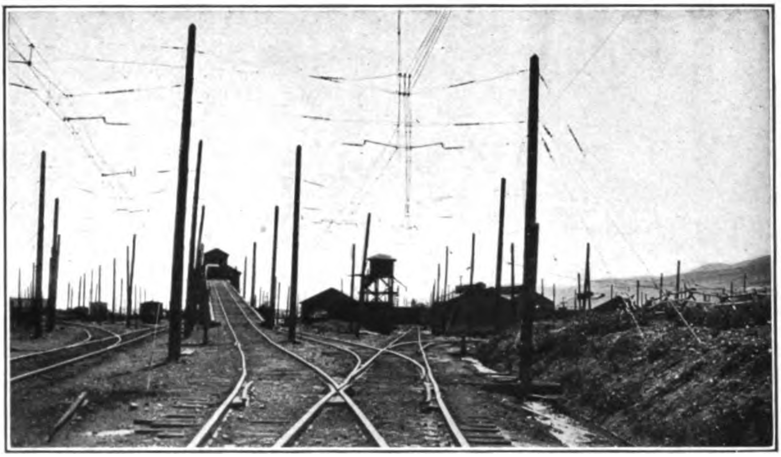
[COX]

FIG. 28—SHEET STEEL BOND PROTECTOR



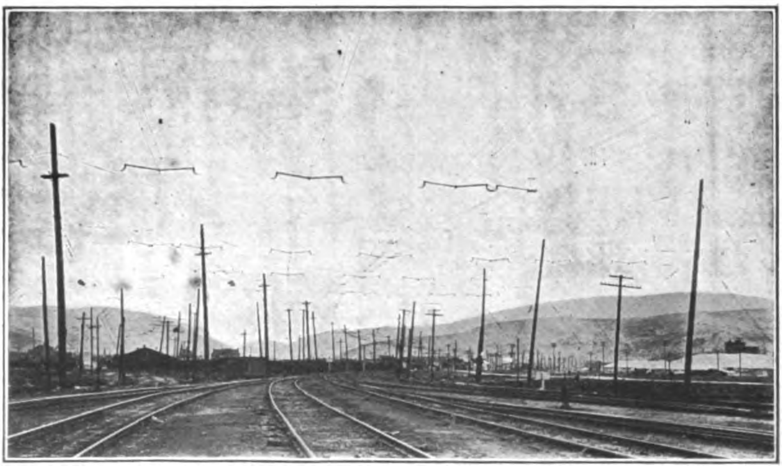
[COX]

FIG. 29—STREET RAILWAY CROSSING—BUTTE



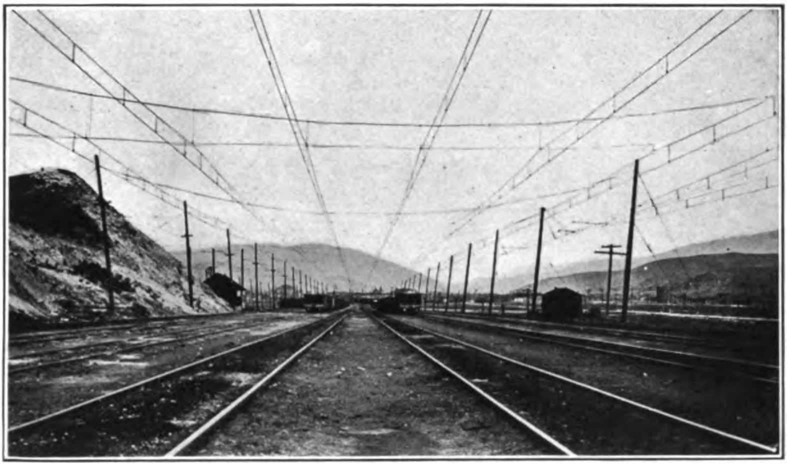
[COX]

FIG. 30—ANACONDA YARD



[COX]

FIG. 31—WEST END OF EAST ANACONDA YARD



[COX]

FIG. 32—EAST END OF EAST ANACONDA YARD

[COX]

FIG. 33—CURVE CONSTRUCTION

The operation of these roller pantagraphs is, therefore, considerably more efficient than had originally been expected.

Two 500,000-cir. mil feeder cables in multiple for the trolley and one 4/0 cable for the track return circuits were run on the trolley line poles between the two substations and other trolley feeders run to the yards which were fed separately or in pairs, as per Fig. 12.

Voltmeter and ammeter readings were taken on a number of trains to ascertain the drop in voltage and energy consumption a summary of which is given in Table VI, from which it will be

TABLE VI.

	Smelter hill service.				Main line service		
	East Anaconda to concentrator				Rocker to East Anaconda		
	Train No. 1	Train No. 2	Train No. 3	Average	Anaconda to rocker	Rocker to Anaconda	Average
No. of cars in train...	18	21	25	21.3	64	57	60
Gross wt. tons.......	1420	1580	1910	1633	1335	4150	
Ton-miles, gross.....	9940	11060	13370	11431	26700	83000	54850
Schedule speed......	16.1	16.2	14.2	15.5	20.1	20.1	20.1
Avge. amperes-total..	580	583	667	610	366	380	373
Avge. volts.........	2327	2277	2276	2293	2325	2345	2335
Avge. kilowatts.....	1350	1327	1518	1398	852	891	872
Max. amperes.......	860	640	800	767	624	640	632
Maximum volts.....	2456	2419	2456	2444	2475	2435	2455
Max. kilowatts......	1951	1500	1733	1728	1368	1510	1439
Total kilowatt-hrs...	580	560	746	629	852	654	753
Watthours per ton-mile.............	61.4	50.6	55.82	55.02	31.91	7.87	13.73
Minimum volts......	2250	2119	2100	2156	2175	2175	2175
Max. drop- per cent..	8.4	12.4	14.5	11.8	12.1	10.7	11.4
Avge. drop per cent...	5.3	5.9	7.3	6.9	6.0	3.6	4.9

seen that the maximum drop in voltage obtained was 14.5 per cent, while the average drop for all readings was 5.6 per cent.

The readings making up the averages given were taken at 30-second intervals for entire trips on locomotives in regular service hauling normal trains under average operating conditions and are, therefore, fairly representative of general results. However, there has been a gradual increase in the weight of the trains which might slightly affect the average drop in voltage.

It may be of interest to note that repair work on the 2400-volt trolley line is done from an ordinary wooden work car with-

out special insulation with full voltage on the line and there has been no serious cases of shock to the workmen.

In wet weather it is not considered safe to work from this car with full potential on the line but there should be little difficulty in constructing a tower car which would make it quite safe under any ordinary conditions.

The writer wishes to thank herein Mr. C. A. Lemmon, Chief Engineer, and Mr. C. H. Spengler, Master Mechanic of the Butte, Anaconda & Pacific Railway, Mr. R. E. Wade, now Ass't. Electrical Engineer of the Chicago, Milwaukee & St. Paul Ry., who had personal charge of the construction of the Butte, Anaconda & Pacific distribution system and Mr. C. J. Hixson and staff for assistance kindly rendered in obtaining the data contained in this article.

To be presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md. July 1, 1915.

CONTACT CONDUCTORS AND COLLECTORS FOR ELECTRIC RAILWAYS

BY C. J. HIXSON

ABSTRACT OF PAPER

A general classification of collecting devices is given corresponding to the existing A. I. E. E. classification of contact conductors.

Contact rail systems and contact wire systems are considered along with their corresponding collectors.

Many data derived from measurements made upon different types of overhead and collecting devices are arranged in the form of curves. The application of these various curves are discussed and the possibilities indicated for selecting other curves to still further express the factors essential to proper collection. This method of attacking the problem is a novel one and it is hoped that those interested in furthering the cause of better collection will be encouraged to assist in making further measurements. Examples are given of constructions where consideration has been given to the factors discussed. Suggestions are made as to profitable subjects for discussion.

THERE has been published within recent years considerable descriptive matter relating to both contact conductors and collectors, but as a rule these two types of apparatus have been treated separately. It seems desirable that they should be considered together, since their successful operation depends upon each of them fitting into the requirements of the other. It is proposed in this paper to discuss the problem of current collection as a whole and in so doing to consider the essential factors for successful operation as well as the ways and means of attaining such results.

In order to avoid confusion it seems essential to classify both contact conductors and collectors and indicate their relation to each other. The A. I. E. E. when defining standards for electric railways, subdivides distributing systems in two classes; contact rails and trolley wires. In the following discussion collectors will be divided into two corresponding classes, namely, contact rail collectors and trolley wire collectors.

The A. I. E. E. classification of contact rails makes certain subdivisions with each of which a distinctive type of collector

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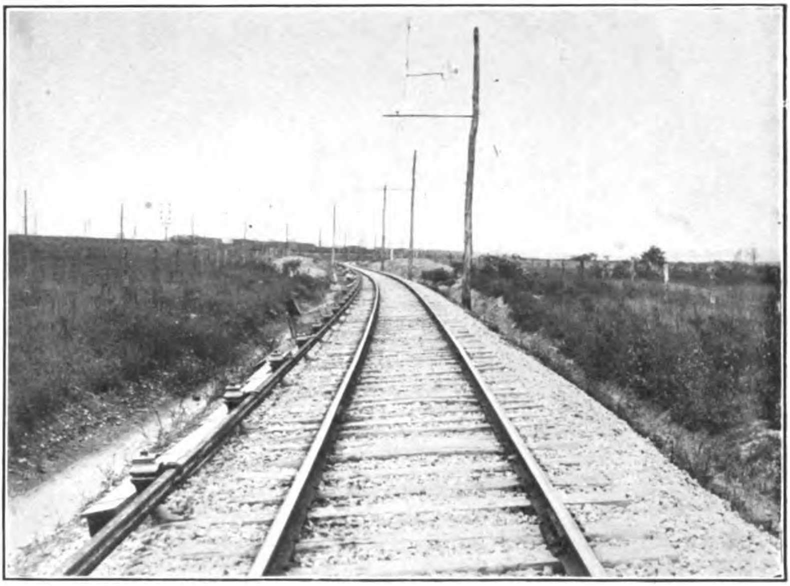
is used. It therefore seems well to follow the same subdivisions for rail collectors, namely, third rail shoes, overhead shoes, center shoes and underground shoes.

As regards the trolley wire, the A. I. E. E. subdivisions direct suspension and messenger suspension, do not require distinctive types of collectors, since any type of trolley is likely to be used with either type of suspension. Common usage, however, seem to have already satisfactorily classified trolley wire collectors into wheel trolleys, roller trolleys and slider trolleys. If wheel trolley be distinguished from a roller trolley by limiting its width to less than its diameter, these three subdivisions become both distinctive and comprehensive for all trolleys. Usage has further subdivided the three types above referred to by utilizing as a basis the general nature of the frame supporting the collecting mechanism directly in contact with the wire, for example, the pole, the bow and the pantagraph. The term which seems to require particular attention at this time is the word pantagraph, used largely in connection with roller and slider trolleys. Although not generally recognized it should be noted that wheel pantagraph trolleys were used many years before either of the types just referred to, and such trolleys are still in regular production. It is therefore apparent that the term "pantagraph trolley" is not definite, since it designates a form common to all three types. Pantagraph is also sometimes used in connection with rail collectors, although if the distinction between rail and wire collectors was commonly recognized its use would probably be unnecessary. For example, the overhead shoe used upon New York Central locomotives was recently referred to as a third rail pantagraph trolley. In order to avoid confusion or the necessity for describing at length each type of collector when referring to it, one of the large manufacturers of electrical machinery was forced, a few years ago, to adopt the classifications as indicated above, *i.e.*, contact rail collectors are divided into third rail shoes, overhead shoes, center shoes and underground shoes, and the contact wire collectors are divided into wheel trolleys, roller trolleys, slider trolleys, with further subdivisions depending upon the nature of the supporting structure.

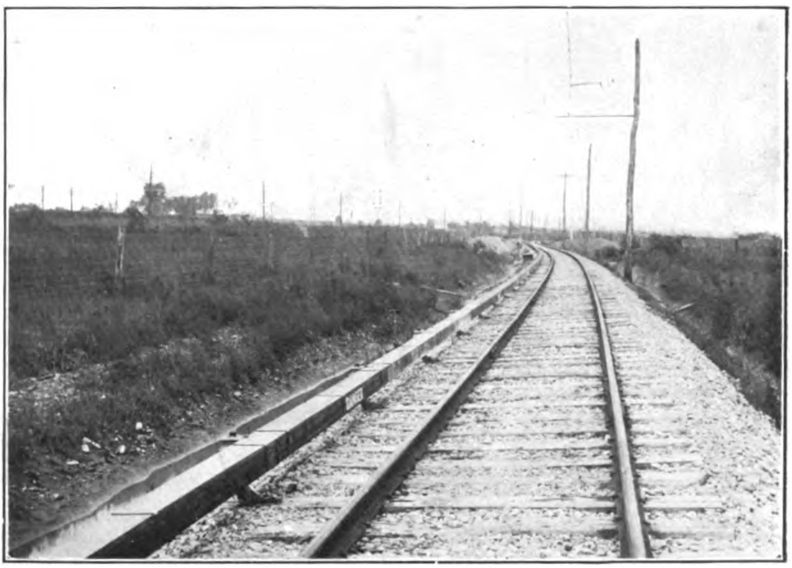
Contact System

There is a tendency to refer to the contact conductor and its collector as a contact system. In fact, it would seem that



[HIXSON]

FIG. 1—SHOWING THIRD RAIL WITHOUT PROTECTION



[HIXSON]

FIG. 2—SAME RAIL AS FIG. 1 WITH PROTECTION

the railway committee in its wording of the subjects for this meeting, has attached this meaning to the terms. Such a construction is at least worthy of the attention of the standardizing committee which might go a step farther and consistently subdivide contact systems into contact rail systems and contact wire systems.

Contact Rail Systems

Rail systems have been in successful operation for many years with great reliability and with a low cost for mainte-

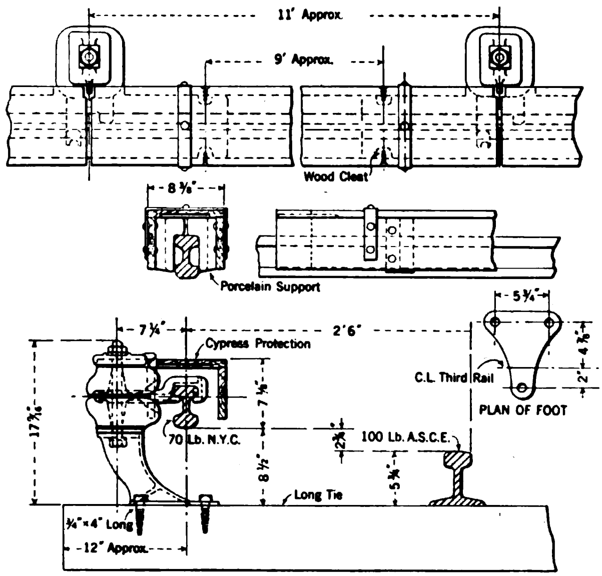


Fig. 4—Third Rail Construction and Location

nance. These systems are particularly adapted for elevated and subway work, and are even better suited for conditions where it is necessary to quickly change from one to the other. High collecting capacity and space considerations as well as there being no necessity for an expensive protection for the contact rail have contributed to the popularity of the rail system for this class of service. The high initial cost, danger to life, difficulties from sleet and snow and complications in yards have been among the factors preventing its wide application to interurban and steam road service. Sleet and snow however, are successfully overcome by inverting the rail and

using an under running shoe but in so doing the cost is somewhat increased.

The increase in operating voltage has materially changed these fundamental considerations. Higher voltages entail greater space and greater clearance distances. If an inverted third rail is to be used for voltages higher than 1000 it is necessary in order not to interfere with the standard car equipment clearances that the location of the insulators be shifted to some other position than that now commonly used.

Several miles of such a type of inverted third rail having the insulator as well as the third rail itself, shifted to a greater distance from the track rail, it being used upon a test railway at East Erie.

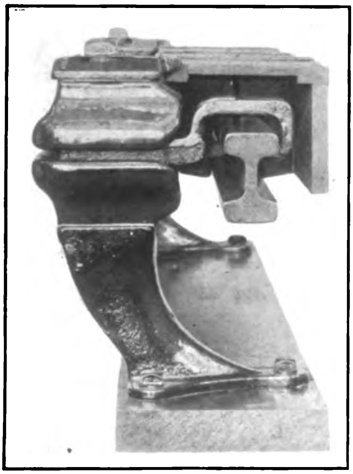
This rail has now been in use for several years and has been satisfactory in every way. The conditions under which it is used are not quite as exacting as those of a road in regular service but the indications are that it would be satisfactory under such conditions. The same type of shoe is used as has been in service for many years for underrunning third rails of lower voltages. The insulation of the shoe beam, however, requires porcelain as a supplementary insulation, and it has been possible to work this out within the limited space in a satisfactory way.

In a series of tests made at Schenectady about a year ago in connection with the use of 2400 volts for an overrunning type of third rail system, it was found desirable to increase the horizontal distance of the third rail from the track by approximately 4 in. more than is ordinarily used for 600 volt work and the height above the running rail was increased by about 6 in. It was found that there were times when full energy was opened by the shoe on the rail and that the arc might whip over to the trucks or other parts of the moving car.

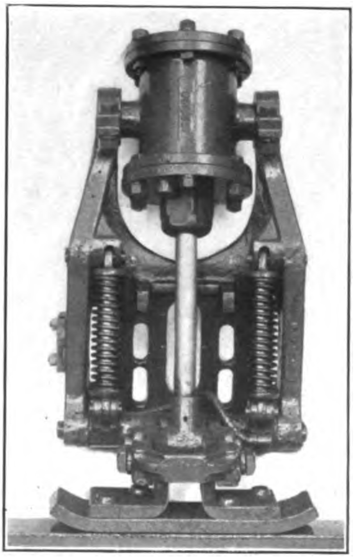
It is interesting to note that a road in the middle west, in connection with the electrification of which these tests were primarily made is now in successful regular service operation.

While there have occurred some short circuits between the third rail and the parts of the moving car this does not appear to be sufficiently frequent to seriously interfere with regular service.

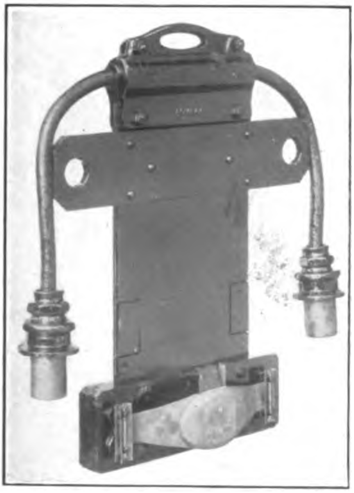
The third rail shoe employed is of a special design due to local conditions and the slipper with its supporting arm is raised and lowered by compressed air. (See Fig. 5.)



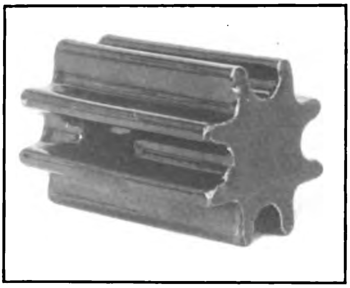
[HIXSON]
FIG. 3—THIRD RAIL SUPPORT AND PROTECTION



[HIXSON]
FIG. 5—THIRD RAIL COLLECTOR



[HIXSON]
FIG. 6—UNDERGROUND SHOE FOR LOCOMOTIVE



[HIXSON]
FIG. 7—PORCELAIN STRAIN INSULATOR

The contact arm is folded up against the side of the car when passing through villages so as not to project and be a source of danger. During the period that the shoe is not in operation energy is supplied through a slider pantagraph trolley.

In general, a 2400-volt third rail is operative and permissible under suitable conditions.

As a matter of general interest at this time, Fig. 6 shows the underground shoe used to supply current to the towing locomotive in service along the Panama Canal.

Contact Wire Systems

Direct Suspension: The direct suspension type of trolley construction has been in use for many years and is standard for conditions involving low speed and moderate amounts of energy. For city service direct suspension with a 2/0 or 3/0 trolley wire is practically universally used in this country, along with a 4-in. or 6-in. trolley wheel provided with graphite bushings. A 4/0 trolley wire was often used in direct suspension with the earlier interurban installations.

For insulation, moulded compound, moulded compound with mica, wood and porcelain are utilized. Some roads utilized moulded insulation suspensions in series with a ball or giant strain insulator supported by a wooden pole. Others have been content to use a wooden pole along with a single moulded insulation suspension. It is rather remarkable how many years of successful service these types of insulation have given. The wood pole is undoubtedly responsible in no small degree for this success. This was quite decidedly shown some years ago when an Italian road attempted to utilize standard American material upon one of its lines equipped with steel poles. The short potential distance within the giant strain insulators located at every pole caused them to act as excellent lightning arresters so that the lightning seemed in most cases to prefer this path to that through the arresters. The difficulty was finally overcome by placing in series with the giant strain insulators, an insulator having approximately six inches of wood.

Since the use of wood for poles and insulators is gradually decreasing it is to be noted that porcelain for both strain and suspension insulators is gradually being adopted. (See Figs. 7 and 8.)

The pole spacing for tangent track has practically been standardized at 100 ft. which is shortened at curves depending

upon the degree of curvature. The type of support is either a cross span wire or a bracket to which is attached a steel strand extending from the end of the bracket to the pole for the purpose of minimizing the hammer blow of the collecting device.

Direct suspension is unquestionably the cheapest type of overhead construction, and has performed a very useful service in keeping down the initial investments upon the early trolley roads, but with the increasing requirements for energy to be collected at high speeds it has become necessary to adopt a more flexible form of construction.

Messenger or Catenary Suspension

The first installations were made abroad and were primarily designed to comply with safety regulations and to provide more convenient means of insulating high voltage trolley wires. The distance between the supporting points of the trolley wire was such that in case the trolley wire broke it would not fall to the ground or upon traffic in that vicinity. It was soon found that this general type of construction had other advantages which, with modifications, rendered it suitable for the increased service conditions. To attempt to even outline the various arrangements of trolley and messenger wires constructed and tried out during the past 15 years would be a task in itself. The diversity in constructions is often such as to indicate fundamentally different conceptions as to what are and what are not desirable factors.

To compensate for the additional expense of messenger suspension it is necessary to definitely know just what benefits are being obtained over those found in direct suspension. There are in existence today certain types of messenger suspensions where it is questionable whether the benefits are equal to the additional money spent. It therefore seems desirable to discuss some factors which have proved to be essential and to indicate along what general lines still further improvements may be expected. It is unfortunate that there is no convenient standard of "successful collection" by which to measure the various degrees of collection but by approximating the life and cost of maintaining the collector and contact wire along with the interest on the investment, it is possible to arrive at a more or less final standard.

If by chance, or otherwise, a high degree of successful collections should be attained, there are available no means for

specifying in definite units the conditions in such a way as to make it possible to reproduce or to maintain this highly desirable state of affairs.

In order to overcome this deficiency it seems necessary to select different kinds or sets of measurements whose values more or less indicate corresponding effects upon successful collections. Although no such selection has been generally recognized, in order to assist in placing the phenomena involved upon some sort of an engineering basis it seems well to indicate how some slight progress at least has been made along such lines.

Uniform Flexibility of Contact Wire

Within the last few years it has come to be generally recognized that "uniform flexibility" is possibly the greatest factor in "successful collection."

When the collector passes beneath the wire, a wave is produced extending one hundred and fifty feet or more, in either direction, depending upon the pressure. The crest of this wave is practically always just over the collector and the height of the wave at any point depends upon how elastic the wire is at that particular point. It is evident that weights due to section insulators, splicing sleeves, hangers, crossings and other devices attached to the wire will produce hard spots directly proportional to their weight.

As regards elasticity at the hanger, not only is the weight of the hanger a factor, but still more important is the weight of the wire which it supports and the lifting action of the messenger wire.

This effect of the messenger wire is of great assistance in increasing the wave height of the trolley wire but unless the hanger is designed so as to permit of a still further free upward movement of the trolley wire after the effect due to the messenger wire ceases, the trolley wave will be restricted by the hanger having to lift the weight of the messenger. It is thus apparent that an improperly designed hanger may result in producing a trolley wire supported by a messenger suspension which will actually give worse collection than a trolley wire supported by a direct suspension system. Installations of this type are in existence and it is possible to show by direct measurements what it is necessary to do in order to correct the major portion of the difficulties with the collector and to put an end to the rapid deterioration of the trolley wire at

points of support. Fig. 9 shows the exact measure of what takes place. The dotted curve shows the normal position of the loaded messenger with the trolley wire at rest. The full line curve above the dotted curve shows the position to which the messenger will rise at the various hangers when relieved of

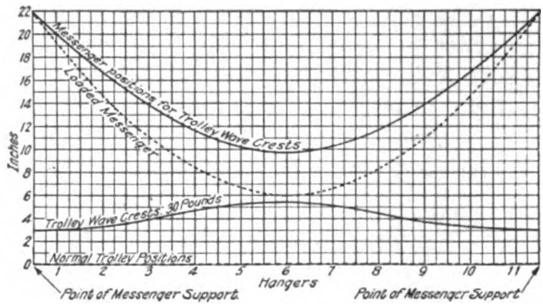


FIG. 9—TROLLEY WAVE CREST CURVE FOR ONE SPAN AND CORRESPONDING POSITION OF MESSENGER

the weight of the trolley wire by the upward pressure of the collecting device. In order to illustrate what takes place, at hanger No. 2, the curve shows that with 30 lb. pressure due to the collecting device, the trolley wave will be about $3\frac{1}{2}$ in. in height. It is also seen, from the distance between the dotted and full line curves for the messenger wire, that at the same

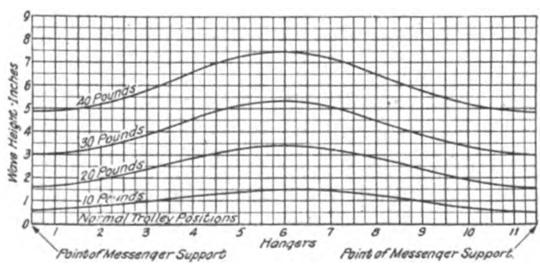
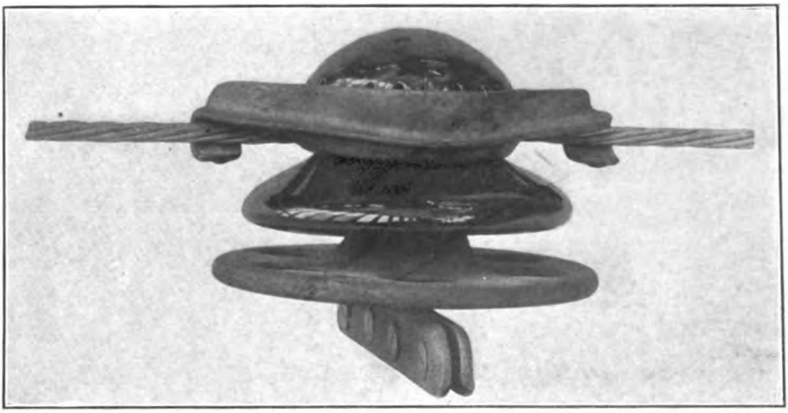


FIG. 11—TROLLEY WAVE CREST CURVES AT DIFFERENT COLLECTOR PRESSURES FOR THE SAME SPAN

time this pressure is applied to the trolley wire the messenger wire will rise 2 in. Therefore, if the hanger is free to continue its upward movement after the messenger has ceased to rise the hanger will be shoved $1\frac{1}{2}$ in. farther up than the position where the unloaded messenger wire stopped going up. Fig. 10. shows a hanger which allows this action to take place.



[HIXSON]

FIG. 8—LINE MATERIAL—1200-VOLT SUSPENSION

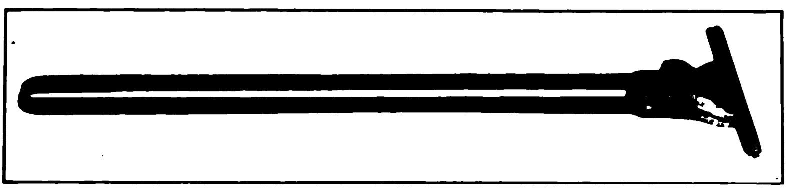
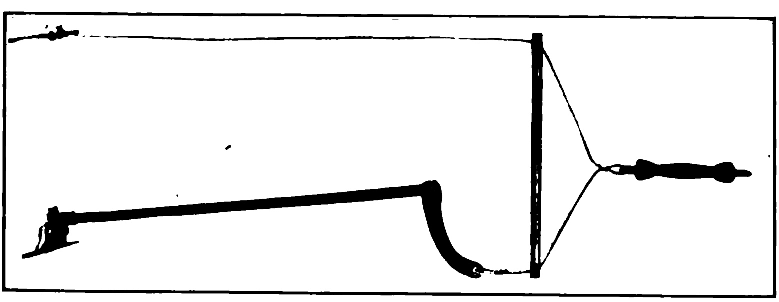


FIG. 10—FORM C H HANGER [HIXSON]



[HIXSON]

FIG. 14—FLEXIBLE PULL-OFF FOR PANTAGRAPH COLLECTOR

Fig. 11 shows how different collector pressures increase the trolley wave crest curves as the pressures increase.

The arrangement and general type of the suspension also

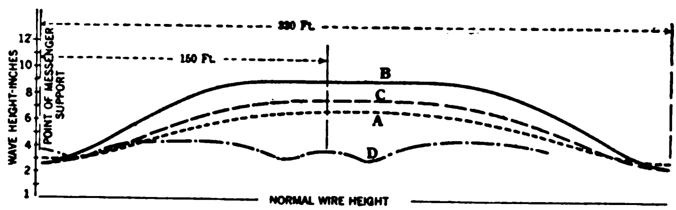


FIG. 12—TROLLEY WIRE WAVE CRESTS UPWARD PRESSURE 30 LB. LOOP TYPE OF HANGER

a—Catenary with auxiliary, 9 ft. sag, 330 ft. span
b —Simple catenary, 9 ft. sag, 330 ft. span.
c —Simple catenary, 5.5 ft. sag, 330 ft. span
d —Simple catenary, 20 in. sag, 150 ft. span

have an effect upon the shape and height of the wave crest curves, that is, upon the uniformity of the flexibility of the trolley wire. Fig. 12 shows wave crest curves corresponding to the construction shown in Fig. 13. It will be noted that although type A has a second messenger wire parallel to the trolley wire which has had the effect of somewhat reducing the distance between the maximum and minimum values that the improvement is not very great over that shown for type C which is for the same length of span but with a single messenger wire. Type D shows the effect of a single messenger when used with a span of 150 feet. It will be noted that in all of them the most rigid portion of the trolley wire is near the point of support and that the difference between them near that point is not very great.

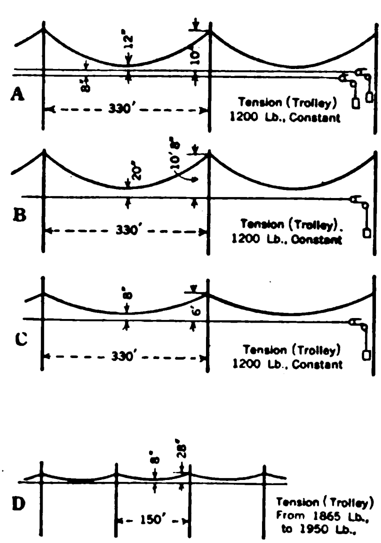


FIG. 13

The considerations discussed as entering into the flexibility thus far have applied particularly to tangent spans which is

the easiest part of the problem. At curves where pulloffs are required the weight of these has to be reckoned with. Fig. 14 shows a very satisfactory arrangement of pulloffs.

In order to obtain the highest degree of uniform vertical flexibility of the trolley wire, each special construction requires a treatment peculiar to itself. Such cases are sidings, low bridges, tunnels, section insulators, splicing sleeves, feeder ears and other devices adding weight to the line. In general, however, it may be noted that with an increasing appreciation of the importance of this factor, means for introducing artificial

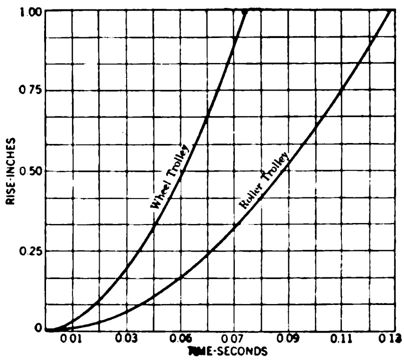


FIG. 15—TIME-RISE CURVES TO COMPARE INERTIA OF TROLLEY BASE AND POLE WITH PANTAGRAPH FRAME—TAKEN AT NORMAL OPERATING HEIGHTS AND 30 LB. UPWARD PRESSURE

Wheel trolley, 12-ft. pole and 9.5-lb. wheel and harp. Roller trolley, roller 5 in. diam. 24 in. long.

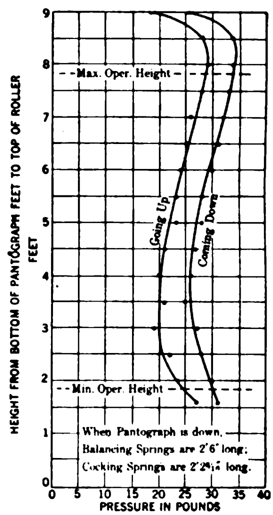
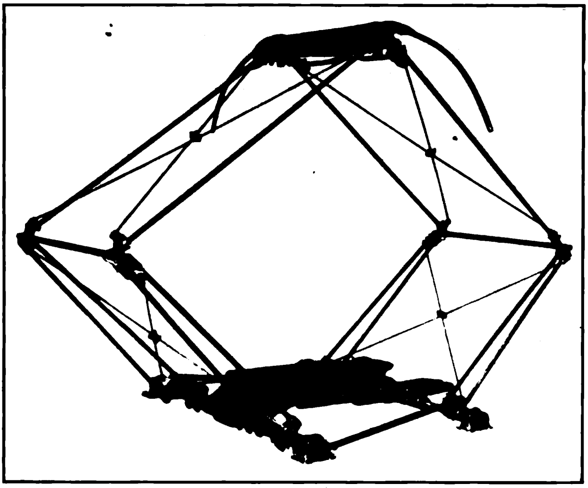


FIG. 17—PRESSURE CURVE —PANTAGRAPH ROLLER COLLECTOR — MAXIMUM WORKING PRESSURE

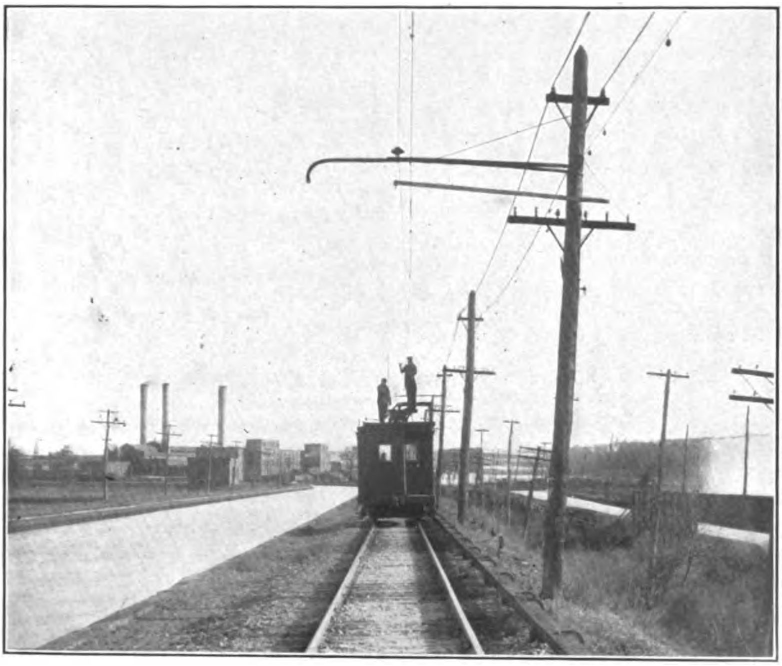
flexibility will doubtless be employed where it is not possible to attain the desired result in some other way. The principle of preventing injury to the wire rather than repairing it afterwards is in line with the general tendencies of these times.

It is to be noted that the data given thus far relative to uniform flexibility have been obtained upon wires at rest. It is appreciated, however, that the inertia of the moving collector, as well as the fact that the weights of the parts constituting the overhead construction have to be accelerated, involve still other factors in successful collection. The exact measures of these are not considered at this time, but it is certain that the



[HIXSON]

FIG. 16—PANTAGRAPH TROLLEY



[HIXSON]

FIG. 21—CATENARY LINE TESTS—BERME BANK TRACK DISPLACEMENT MEASUREMENTS

values of these factors are closely interlinked with the characteristics of the collection device.

Trolleys

It is known that the pole-supported trolley wheel is much quicker in its action than the heavier roller and slider pantagraph trolleys. Fig. 15 shows the distance-speed relation of these two types of collectors. The roller trolley referred to is shown in Fig. 16.

Since the trolleys must operate over a range in some cases

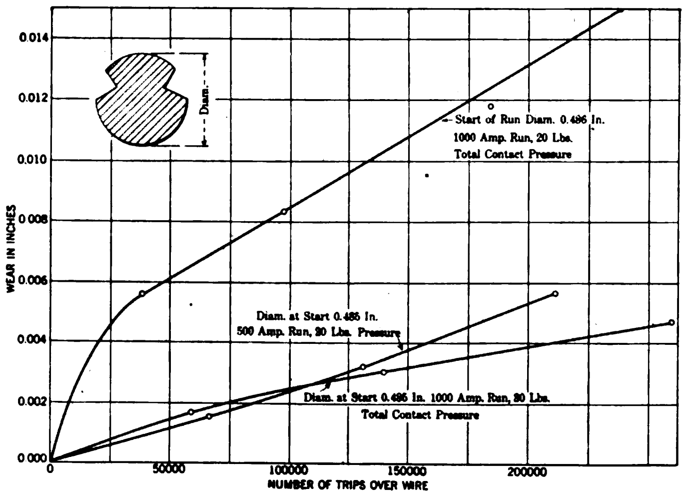


Fig. 18—Sliding-Contact Trolley Current Collection

New wire at beginning of run
Wear on 0000 grooved copper trolley wire
Double-pan collector with eight 1 in. copper contact strips
Reciprocating motion, 4 ft. travel, 100 times per minute.
Lubricated with 2/1 mixture of 107 motor grease and graphite, by weight.

as great as 9 ft. it is important to know what the pressure against the trolley wire is at various heights of the collector. Fig. 17 shows this relation for the roller trolley.

When speeds of 60 mi. per hr. and currents of 2000 amperes and more have to be considered, it is found desirable to employ a slider type of trolley. In order to investigate just what the effect of a slider would be upon the wear of a trolley wire between points of support, a series of tests were made in a testing machine in which the collecting strips were moved back and forth a definite distance under trolley wires. Figs. 18, 19, and 20 show the results of these tests.

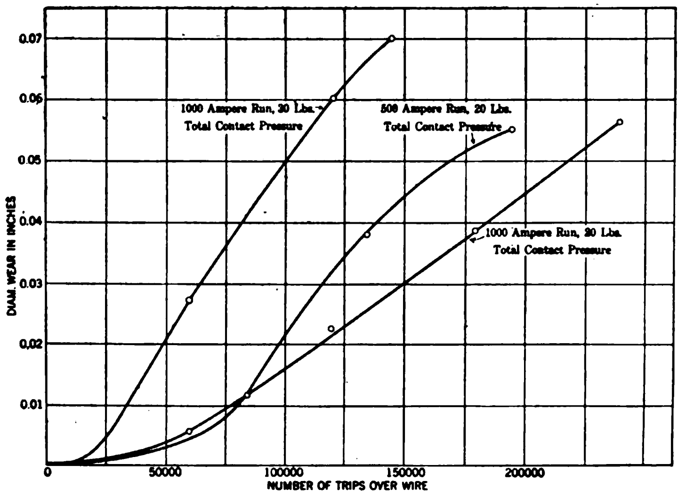


FIG. 19—SLIDING-CONTACT TROLLEY CURRENT COLLECTION

Wear on 0000 grooved copper trolley wire,
Double-pan collector with eight 1-in. copper contact strips
Reciprocating motion, 4-ft. travel, 100 times per minute.
No lubrication.

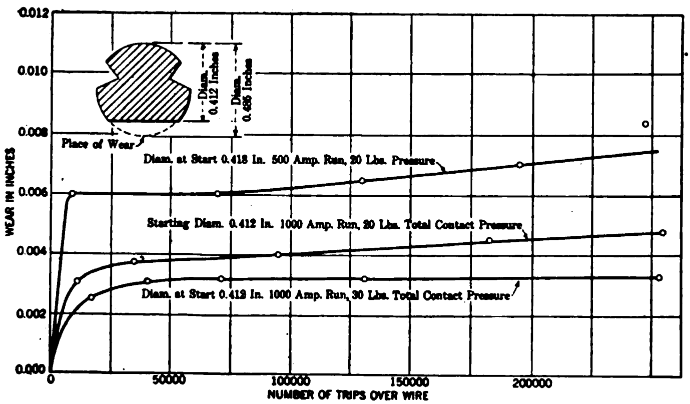


FIG. 20—SLIDING-CONTACT TROLLEY CURRENT COLLECTION

Wire worn off about 0.074 in. at start of run.
Wear on 0000 grooved copper trolley wire.
Double-span collector with eight 1-in. copper contact strips.
Reciprocating motion, 4-ft. travel, 100 times per minute.
Lubricated with a 2/1 mixture of 107 motor grease and graphite, by weight.

Double Trolley Wire

Along with this problem of high speed and great capacities it was found desirable to employ two trolley wires hung side by side with the supporting points so spaced that the hangers on one wire come midway between the hangers on the other wire. This results in a great improvement in the uniformity of the flexibility of the trolley wire as well as an increase in the collecting and conducting capacity.

Effect of Wind

The effect of wind upon the overhead construction has always been a subject of considerable uncertainty, and in order to definitely measure as far as possible such effects upon different

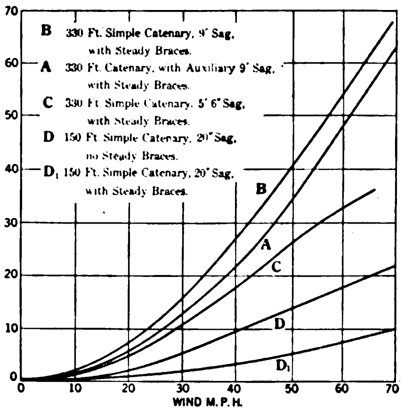


Fig. 22—Trolley Wire Displacement Due to Wind

types of overhead constructions, a series of tests was made, in which weights were attached at each hanger which corresponded to different wind pressures. The general arrangement of the weights are shown in Fig. 21. The effect of the wind upon the constructions are shown in Fig. 22.

In conclusion it might be said that there are many other problems which might be discussed with profit, among which, in connection with the overhead construction might be mentioned:

1. The use of deflectors or other devices at sidings.
2. The best method of section insulation.
3. Convenient means for taking up slack at anchorage vs. automatic take-up devices in conjunction with the introduction, artificially, of elasticity into the line.

4. Elimination of splicing sleeves, particularly of the soldered type.

5. The necessity for staggering the trolley wire and frequency of steady braces against sections of the wind.

6. Construction at tunnels and bridges both as regards insulation and collection.

7. The necessity for uniformity in the safety factors allowed in different parts of the country.

8. The best method of arranging "ticklers" for warning the brakeman of approaching bridges or tunnels upon electrified lines.

In regard to the problems which might be discussed in connection with trolleys might be mentioned:

1. The desirability of the air-locked vs. the air-raised type.
2. Height of the trolley wire.
3. Width of contact strips.
4. Shape of horn.
5. Clearance allowances between trolley and permanent way.

The author desires to express his appreciation of the assistance of Mr. G. W. Bower and Mr. C. G. Lovell in the preparation of this paper.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

THE TREND OF ELECTRICAL DEVELOPMENT
President's Address

BY PAUL M. LINCOLN

AN ANNUAL address by the president of our Institute is more than a perfunctory affair. It is a constitutional requirement. It is enumerated specifically in our constitution among the duties of the president—"He shall deliver an address at the annual convention."

It has occurred to me that in my address on this occasion it might be well to trace the progress of some of the developments and practises that have marked the path that the electrical engineer has traversed in the past, with a view of obtaining some idea, possibly, as to whither these paths may lead us in the future. Insofar as this method incorporates a review of the past it presents no particular difficulty; but when it involves a prognostication of what a continuation along any particular line of development will finally lead to, it delves somewhat into the realms of prophecy. I realize full well that anyone who attempts to deal in prophecy among the inventions and developments of this day and age is running a grave risk, and I therefore do not propose to wander far from what I conceive that the trend of present development will carry us toward in the future.

In the matter of efficiency, it has always been recognized that electrical apparatus is in a class by itself. Mechanical energy can be converted into electrical by a generator, or *vice versa*, by a motor, at an efficiency ranging up to as high as 97 per cent, or even more in the most favorable cases. I think it is a safe statement to say that the average efficiency of the conversion of mechanical energy into electrical by generators, or electrical energy into mechanical by motors, including all sizes under actual operating conditions, will reach 90 per cent. There are, of course, many cases where the efficiencies are lower than 90 per cent. On the other hand, there are many cases where the conversion is carried on at much higher

efficiencies, and I believe that the assumption of 90 per cent as an average figure is not far from the truth. Owing to the fact that the size of the average electrical generator is much greater than that of the average motor and that it is possible to operate the generator at higher average loads than in the case of the motor, it must be apparent that the average efficiency in converting mechanical energy into electrical energy is higher than in the reconversion of this electrical energy back into mechanical. The average generator efficiency is undoubtedly well above 90 per cent, while it is doubtful if the average motor reaches so high a figure. However, the general conclusion I would draw from these figures is not modified by this difference between generator and motor. This conclusion, which must be apparent to anyone, is that no development of a revolutionary character can be looked for in this respect. Our ability to convert mechanical energy into electrical, or *vice versa*, has reached so high a value that even if we could obtain perfection itself we could add only a matter of 10 per cent to what we have already accomplished. This conclusion must hold unless the law of conservation of energy is revoked, and I am not predicting any suspension of that law.

When we come to deal with the efficiencies by which electrical energy in one form is transformed into electrical energy of another form, efficiencies are found to be still higher. The efficiencies of some of our larger transformers, for instance, exceed 99 per cent. The synchronous converter, in which alternating current is changed into direct, attains efficiencies approaching 98 per cent. It is evident that perfection itself could not add greatly to existing performances and hence nothing revolutionary may be expected along this line in the future.

When we come to consider the prime mover, we find a marvelous improvement in recent years. Taking up first the waterwheel, the early attempts to develop power at Niagara Falls constitute a significant commentary upon the status of the waterwheel at that time (the late 60's and the early 70's). About that time the building of what is now known as the Schoellkopf canal at Niagara Falls made available a head of about 215 ft. at the edge of the cliff below the falls on the American side. Of this 215-ft. head, these earliest wheels used only some 15 or 20 ft. for some of the least progressive, and from there up to possibly 40 or 50 ft. for the more progressive. After passing through the wheels under this head, the water was

then discharged at the face of the cliff and fell uselessly for the remainder of the distance, much to the detriment of the scenic beauty of the bank. And not only was it impossible at that time to obtain waterwheels that would work under more than these very limited heads, but the efficiencies of such as were used were very far below those attainable now. Today, waterwheels have no limit in head, except that imposed by the strength of available materials, and efficiencies ranging up to 90 per cent are expected as matters of course. Improvements in waterwheel design will, of course, continue, but perfection itself would add but a matter of 10 per cent to the best of our modern practise, and not to exceed 20 per cent to 25 per cent to the worst. Therefore, in waterwheels, as well as in motor and generator practise, we are approaching the limits set by natural laws almost as closely as human ingenuity can be expected to attain. No startling or record-breaking developments need be expected along these lines so long as the law of conservation of energy holds.

In thermodynamic engines too, the last few years have seen marvelous improvement. The reciprocating engine of Watt has largely given place in recent years to the steam turbine, and the use of the turbine has enabled us to attain efficiencies in thermodynamic conversion that were out of the question with the reciprocating engine of Watt. In the thermodynamic conversion the law of conservation of energy takes a peculiar form. No conceivable method of thermodynamic conversion can begin to transform all of the energy contained in a lump of coal, for instance, into dynamic or mechanical form. If the heat contained in the coal is used to heat a fluid and that fluid is used in a thermodynamic engine, the maximum mechanical energy that can be taken from that engine can bear no greater ratio to the total heat imparted by the fuel to the fluid than the actual range of temperature used in the engine does to the maximum absolute temperature of the fluid as it enters the engine. The efficiency which would result by the use of this ratio of temperature ranges is that which would result if what is known as the "Rankine cycle efficiency" were 100 per cent. Some of the best of our modern steam turbines have attained to as high as 75 per cent—or possibly a little more—of this Rankine cycle efficiency. In these most perfect engines, therefore, perfection itself would not add more than 25 per cent or such a matter. It should be particularly borne in mind that this

statement is true only of the best of modern practise. It is not true that the average of modern practise attains anywhere near this degree of perfection. It is only with prime movers of the largest size and most modern design and construction that so close an approach to the ideal can be attained. As capacity is reduced it becomes rapidly more and more difficult to attain the higher degrees of economy in thermodynamic machines. This must always remain one of the potent factors in the economics of power supply. It is, and undoubtedly always will be, one of the fundamental reasons why central station supply of electric service must prevail as against isolated plant supply for the same service. The central station can, of course, use units which are very large in comparison, and can be worked at much higher average loads than must necessarily be the case with an isolated plant.

One obvious means that has been suggested to improve the efficiency of the thermodynamic engine is to increase the temperature range through which the working fluid is used. When using water or steam as the fluid in our heat engine, there are certain practical limitations to the temperature range which is available and the temperature range cannot be materially extended over the best of modern practise. The only two ways to extend this temperature range when using steam are to increase the superheat or increase the pressure. Increasing the superheat over the best modern practise does not promise results commensurate with the expenditure of heat to obtain this superheat, since increasing the temperature at one end of the heat cycle simply involves a loss in the efficiency at the other end. There is a rather definite limit to superheating of steam beyond which it is useless to go. Increasing the steam pressure does promise results, and it is probable that the tendencies for the future developments in thermodynamic engines will be toward these higher steam pressures.

Another promising method of increasing temperature range is that to which attention has been called during the last year or two by Mr. W. L. R. Emmet of Schenectady. He has called attention to the advantages of using mercury as the working fluid in a heat engine for temperature ranges above those available with steam. After working the mercury through a given temperature range, the heat remaining in the mercury is transferred to water and the steam thus made available is again worked through a lower temperature range. The ad-

vantages of this are that the steam is in practically all respects the same as in standard steam turbine practise and the mercury cycle is closely similar to the steam. Additional energy is made available from the same amount of initial heat, due to the greater temperature range obtainable by the use of the mercury. The main disadvantage is the poisonous nature of mercury vapor and the difficulty of absolutely preventing its leakage at the high pressures and temperatures of the mercury boiler. These practical difficulties make it too early to predict whether or not this method will work out as a feasible solution of the thermodynamic engine problem. However, it can be said that without some such method or device, the future is apt to bring no revolutionary improvements in thermodynamic engines over the best of modern practise. Improvements of course will undoubtedly continue to take place, but it cannot be hoped that the improvements of the future will be of the same revolutionary character as the improvements in the thermodynamic engine which have taken place within the last 10 or 15 years. Here again we are approaching so close to the law of conservation of energy that it is safe to make a prediction of this nature.

In the matter of size and capacity of generating units, it can safely be said that this is a consideration that will hereafter be fixed by the conditions to be met and not by any inherent limitation in our ability to produce units of any desired output. We now have units of 30,000 kw. capacity in service and still larger ones projected, and no limitations of design or material appear of such a nature as to place a stop to further progress along the same line.

At Omaha, in June 1898, the then president of our Institute, Dr. A. E. Kennelly, made an inaugural address upon the topic, "The Present Status of Electrical Engineering." This address constitutes a very convenient milestone by which to judge our progress since that time, and in this address I will take the liberty of quoting freely from this 1898 address of Past President Kennelly. In the matter of generator sizes, he says, "In 1884 a 50-kw. dynamo was considered a large machine, while a 100-kw. Edison steam dynamo was justly called a 'jumbo'. At present the largest size of generator built or building is of 4600-kw. capacity." In the 14 years from 1884 to 1898 the maximum size of generator therefore increased 46-fold, while in the 17 years since that time, the increase has only been about 7-fold. While the increase in capacity therefore

has been a marked one, the rate of increase has not been so rapid during the last 17 years as it was in the previous 14 years, a result which naturally might have been anticipated. The future will undoubtedly continue to produce larger and larger capacity machines, the limit as to size being dictated by plant capacity and economic considerations and not by any inability to produce the larger sizes.

In the matter of selling price of such apparatus the following extract from Kennelly in 1898 may be of interest: "The price of dynamos in 1882 was about 20 cents per watt of output, while dynamos of similar running speed for comparatively small sizes without switchboards now cost about 2 cents per watt." The speed and size of these units is not mentioned, but it may be said in comparison that nowadays prices are frequently quoted below one-half cent per watt. In this respect again, the improvement in the last 17 years has not been so marked as it was in the 14 years previous, a result that is only to be expected. In the next succeeding period it is probable that a still smaller degree of improvement will occur. We are approaching a saturation point in this respect.

It may be well to point out some of the reasons for this approach to saturation in the matter of costs. The two fundamental costs of electrical apparatus are those of labor and material. In regard to the item of labor, I submit that it is safe to predict that the tendency for the future will be for the cost of labor to increase rather than decrease. Economies in the use of labor will undoubtedly take place by the introduction of the methods of scientific management, etc., but these need not be expected to be revolutionary in character so far as cost of apparatus is concerned. The tendency of the labor item will unquestionably be toward appreciation rather than depreciation.

In regard to the item of material, modern design has approached very close to the physical limits of available materials. Take, for instance, the property of permeability possessed by irons. With higher permeability, making available greater flux densities, the cost of electrical apparatus might be considerably reduced. That the future will bring some improvement in this respect is unquestionable; but it is further highly improbable that this improvement will be of such a revolutionary character as to cause any sweeping change in the cost of electrical apparatus.

The hysteresis and eddy current losses that take place in irons and steels that are subjected to varying magnetic fluxes constitute another of the limits encountered in the design of electrical machines. Marked progress has been made in this respect in recent years. Our modern transformer steels in the matters of losses and iron aging qualities show a vast improvement over those formerly available. Unfortunately, these improvements have so far been accompanied by a decrease in permeability which is highly objectionable, particularly in rotating machinery. Unquestionably, further improvements will be made in the magnetic qualities of our irons and steels, but these improvements will probably make no revolutionary change in the costs of electrical apparatus.

The conductivity of copper and other metals is another physical property that sets a limit to the output and cost of our electrical apparatus. Apparently we have reached a definite limit in this respect. The conductivity of the copper of commerce is within an extremely small percentage of that of pure copper and we cannot expect to obtain a higher conductivity in copper than that of purity. There remains, of course, the possibility of using some metal other than copper, but at this present time there is very little promise in that possibility. There is apparently no metal that even approaches the space and cost characteristic of copper that makes it so essential to the construction of electrical apparatus. Aluminum is a competitor only when the volume of the conductor is not an essential element in design, as a transmission line and the like.

One of the most pressing of our existing limitations to a reduction in cost of electrical apparatus is that fixed by temperature rise. The output of a piece of electrical apparatus increases with the temperature rise, and the temperature rise in turn is dictated by the point of balance between the rate at which heat is put in and that at which it is taken out of a machine. The rate at which heat is put in depends largely upon such physical characteristics as hysteresis and permeability of iron and conductivity of copper, which characteristics are already being crowded to the limit by our modern designs. The rate at which heat is dissipated depends upon the efficacy of the ventilation methods used, and in this particular there is a considerable opportunity for improvement. The methods and devices for taking heat out of machines are just as important, when con-

sidering temperature rise, as the prevention of heat from entering. While there is unquestionably room for considerable improvement in this particular, there is a question as to whether it will cause any material reduction in the cost of such apparatus. The additional cost of applying the more efficient methods of dissipating heat will go far toward nullifying their tendency toward a reduction of cost.

However, there is one line of development that does promise some reduction in cost, and that is the tendency toward higher operating temperatures. In the past, the maximum operating temperature has been fixed by the disintegrating point of fibrous insulation, and this point has placed a very definite and logical limit to temperature rises in such machines. However, when types of insulation are used which do not have this definite temperature of disintegration, this reason for such a temperature limit disappears. Just how far we can go in apparatus temperatures without exceeding the safe limits of these heat-resisting insulations is as yet problematical. However, a limit to an indefinite extension in this direction is set by the temperature coefficient of copper conductors, the property that causes the resistance to rise with increasing temperature, thereby causing still higher losses and in turn still higher temperatures. If we go high enough, we will reach a point of unstable equilibrium in this temperature rise curve, where the apparatus will literally and automatically "burn out." This point is, of course, far above anything that is projected at the present time, but while we are looking for limits, we might as well recognize that such a one exists.

In the matter of power production therefore, although we have steadily improved in the past, both as to costs and as to performance, and although we may expect to continue this steady improvement in the future, we must not expect that these improvements will be of the same revolutionary character as they have been in the past. We can see ahead of us a definite limit beyond which it will be impossible to improve the methods of power production now in use. I do not mean to say that there will be no new or revolutionary methods developed in the future, but so long as we continue to get our power from falling streams and burning coal, we need not expect to see the same radical improvements in the future as have distinguished the past. To illustrate my point more fully, let us consider the nature of a water power. Water is evaporated by the

action of the sun and is carried miles above the earth into the clouds. Here it is precipitated in the form of rain or snow and falls on the earth. The streams carry this water back to the ocean and it is then ready to repeat the cycle. Our existing water powers utilize an almost infinitesimally small part of this water over an almost infinitesimally small part of the total height to which the sun carried it. Insofar as is concerned the water we use over the head through which we use it, we do fairly well, but the part of the sun's energy which we thereby realize is so infinitesimally small that it puts us to shame. Some Westinghouse or Edison of the future will show us how to use the sun's energy directly. The point I wish to make is that the revolutionary improvements in power production methods of the future must come in a fundamental change of method rather than in the continued improvement of existing methods.

So much, then, for the methods of producing power. In the matter of utilization of power a few comparisons with the past may not be amiss. As indicated early in this address, the modern motor has reached a stage, insofar as efficiency is concerned, such that little improvement may be expected. We are within a comparatively small percentage of perfection in this respect. The progress of the future will undoubtedly come from improvements in methods of application, and in this direction the field is inexhaustible. For instance, the problem of applying electrically the large amounts of power which are demanded by our modern railroad trains has not yet received a solution which is satisfactory to all concerned. That the problem will be solved there is no doubt in my mind, but just how, is a question that I do not propose to discuss in this address. However, this is only one of the many problems that confront the electrical engineer. The devising of methods for the application of electricity to our modern industries constitutes the occupation of no small part of our fraternity; as witness the many pages in our PROCEEDINGS that have been occupied during the past years by the activities of the Industrial Power Committee. It is along this line that we may expect much of what the future may have to offer us of a revolutionary character.

In the field of electric lighting there have been developments of importance. After the telegraph, in point of time, the electric light was the first practical application of electricity.

Most of our modern development in electrical engineering

has taken its initiative from the supply of electric lighting to our communities. In this matter of electric lighting let me quote again from Kennelly's 1898 address: He says, "The price of a 16-candle power incandescent lamp 16 years ago was about $1.00. Now it is about 18 cents. The best lamps at that time, under laboratory conditions, gave about 0.28 mean horizontal normal British candle power per watt, and under commercial conditions about 0.20. The highest pressure for which they could then be obtained was about 110 volts. At the present time, lamps are obtainable giving normally 0.4 mean horizontal British candle power per watt, while under commercial conditions the average lamp normally develops about 0.25 candle per watt. They can also be obtained (at 0.25 candle per watt) for pressures up to 240 volts, and are frequently installed on 220-volt mains."

Kennelly therefore records an improvement in 16 years of about 50 per cent in cost of lamps to the consumer and about 50 per cent in efficiency. The introduction of the metal filament lamp has enabled us today to record a much greater rate of improvement in efficiency than Kennelly did. He reported an improvement of about 50 per cent in efficiency in the 16 years previous to 1898. In the 17 years since Kennelly wrote, we have improved our maximum efficiency about 1000 per cent, an advance which is truly marvelous. But here is a field where we have a long way to go yet without reaching a possible limit. It is true that the melting point of the now available materials seems to place the limit of lamp efficiency at a point not much higher than that which we have at present. However, when we come to compare the efficiencies of even our best lamps with that attained by the fire-fly it is evident that we still have a long way to go before we have reached perfection.

In the matter of power transmission, progress during the past few years has been remarkable. In 1898 the record reads:—"The electric transmission of the power of falling water is a branch of engineering that has come into service since 1884, and is making rapid strides, owing to the recent successful employment of high voltages and multiphase alternating currents. It has been estimated that about 150,000 kw. of this class of machinery is installed on the North American continent, commercially transmitting power to various distances up to 85 miles, at various pressures up to 40,000 volts." Since Kennelly wrote, 17 years ago, the maximum transmission volt-

ages have gone up about $3\frac{3}{4}$ times; the maximum then was 40,000 and now is 150,000 volts. The maximum distance of transmission has gone up about $3\frac{1}{2}$ times, 245 miles as against 85, and the installed capacity of water power plants on the North American continent about 9 times, 1,350,000 instead of 150,000 kw. Kennelly also mentions in his record that "insulation testing sets have been made for producing alternating pressures up to 160,000 volts effective." In this respect we can go at least 10 times better than he reported, 1,000,000 volts from transformers having been made available on more than one occasion, and in some cases the voltage available from transformers has been pushed even higher. This matter of power transmission is a branch of our industry wherein the progress of the last 17 years since Kennelly made his record has advanced with probably greater rapidity than in any other branch. I feel very sure that the president of our Institute who comes along 17 years hence and compares the then conditions with my record will not be able to claim any such advance as that we now may claim over 1898. This follows because we are approaching some fairly well defined limits in these matters. For instance, in the question of increasing transmission voltages we are close to the corona limit. The appearance of corona in the transmission line means the continual loss of power and therefore corona cannot be tolerated to any appreciable degree. There are, of course, methods of increasing the voltage range somewhat before corona is produced, such as increasing conductor diameter, but it can be readily seen that the limits of such remedies will be reached long before transmission voltages have increased by the same ratio as they have in the past 17 years.

Another limit that we are approaching in the matter of power transmission is the economic one. Transmitted power costs more than that generated at the point of delivery on account of the cost of and the losses in the transmission line. There obviously is a limit to the investment that can be made in transmission lines and still be able to supply power with the same economy as it can be generated upon the ground. This consideration, coupled with the rapid advance in methods of generating power from steam, has in my mind placed an economic limit to the transmission of water power so that we cannot expect any such advances in the future as the past 10 or 15 years have given us. That there will continue to be

improvement and advance, no one can doubt, but its rate will certainly be diminished.

Transmission by high-voltage direct current has received some attention of recent years. While there is no question but that the problems of pure transmission are much simplified by the use of direct current, the accompanying problems of the generation and utilization are so much intensified that nothing is to be gained in this manner. I would predict no material advance for the future in direct-current transmission of power unless some means, as yet undeveloped, is found by which its generation and utilization are made easier and safer than is possible at present.

And so we might go on indefinitely and draw comparisons with past practises. Always we find progress, always also we find that the rate of progress is not so high now as it was in previous years. This is but the working out of a natural law. Electricity is no longer the infant that it was formerly pictured, and cannot be expected to continue the rate of growth of the infant. It is attaining the vigor and strength of manhood. It is contrary to natural law that either a child or an industry can have rapidity of growth and at the same time strength and stability of character. Unquestionably the rapidity of our development is not so great now as it was when Kennelly spoke in 1898, and in this respect we are but following a natural law. At the same time, our vocation is acquiring a stability and permanence that are absolutely incompatible with the rate of growth that characterized its earlier years.

An address delivered at the Annual Meeting of the American Institute of Electrical Engineers, New York, May 18, 1915.

HOW BELL INVENTED THE TELEPHONE

BY THOMAS A. WATSON

IT IS my privilege and pleasure to speak to you of the invention of the telephone, with which event it was my good fortune to be connected, my association with Prof. Bell as his mechanical expert having brought me into close touch with nearly all his experiments both before and after his great discovery.

I shall try to tell the story as it impressed itself on my mind in those early days when I was a young man of about 20, just out of my apprenticeship as a maker of electrical apparatus, intensely interested in my work, and with a full share of youthful enthusiasm. In my story, I shall not use the terms and formulas of modern telephony, for they would certainly be out of place in speaking of the time when that science, now so complex, was contained in one human brain.

It was in the year 1875 that the telephone emerged from the mists of the unknown into a world that had no dynamos, no electric motors, no trolley cars, no storage batteries, no electric lights, no wireless telegraphs, no steam turbines, no gas engines, no automobiles, and no professional electrical engineers, for none of our universities had up to that time offered to their students electrical courses.

Those men we all revere—Davy, Faraday, Henry, Volta, Oersted, Ohm, Maxwell, Thomson, and others, had already laid the deep and sure foundations on which modern electrical practise has been built, but apart from the telegraph, electricity, as a practical utility, had scarcely entered the daily life of man.

In 1874 in place of the great electrical manufacturing establishments of the present day, there were a few crude little work shops scattered throughout the country, eking out a precarious existence chiefly by making telegraph instruments, school apparatus, call bells, annunciators, etc., and also experimental apparatus for the many inventors who utilized the meagre facilities of those shops to put into practical shape

their electrical projects. This was an important feature of the electrical activities of that time, for although the work of these men was for the most part obscure and unfruitful, they were undoubtedly the leaders in the great awakening to the practical possibilities of electricity that began about the time of which I am to speak, and which has since then produced such tremendous results.

In 1874 I was employed as a mechanician in one of the most important of these shops in the United States. It was in Boston, owned and operated by Charles Williams, trained as an apprentice of that famous electric antique, Daniel Davis. Williams, when he was very busy, employed about fifty men, but while I was with him his works seldom ran at more than fifty per cent of their normal capacity. His tools were almost entirely hand lathes. His shop possessed no milling nor screw machine nor had it even a metal planer. Practically all his work was done on hand lathes or with the vise and file. He had one 16-inch engine lathe, to operate which was the highest earthly aspiration of his apprentices. It wasn't in good condition, for one of the boys had run a boring tool into the hole in the spindle so the live center wiggled badly, but we managed to do some rather difficult and accurate work on it in spite of its defects.

Into Williams's dismal and poorly equipped shop Alexander Graham Bell came, in the year 1874, to get his "harmonic telegraph" invention put into practical shape. J. B. Stearns had just then perfected the " duplex telegraph " which would send two messages simultaneously over a single wire. Prof. Bell was sure his invention would send at least six or eight. My work at Williams's at that time had become largely making experimental apparatus for inventors and I am glad to say that Prof. Bell's work was assigned to me.

Prof. Bell was very enthusiastic over the possibilities of his telegraph on which he had been studying ever since his arrival in the United States in 1872. Its operation depended, as you know, on the fact that a stretched string or a tuned reed will be set into vibration when impelled by a succession of impulses corresponding in number per second to its pitch. Here is one of Bell's telegraph receivers. It is a simple electromagnet with a strip of steel clamped to one of its poles, having the other end of the strip free to vibrate over the other pole. The transmitter had the same parts with the addition of contact

points that kept its steel reed vibrating when the current was connected and, making and breaking the main circuit at each swing, sent an intermittent current pulsing into the line and through the distant receivers. Each receiver reed was expected to respond to impulses of its own pitch and to ignore those of any other pitch.

I made for Prof. Bell six or eight of these transmitters with their reeds tuned to different pitches and the same number of receivers with their reeds tuned to correspond. Their test, however, gave results sadly out of accord with his expectations and a long series of experiments followed with rather unsatisfactory results.

The saying so frequently offered for our consolation: that we profit more from our adversities than we do from our successes, was certainly applicable to Prof. Bell's case at this time, for had the rhythmic intermittent current that actuated his telegraph accomplished the result he expected and brought him fame and fortune, he might not have been impelled to seek a better form of an electric vibration and so might have missed the discovery that has since placed his name among the immortals.

Prof. Bell's experiments with the apparatus I made for him soon revealed the serious defects of the intermittent current wave. He was able to transmit with it two or three messages, each on a different pitch, with a reasonable degree of certainty, but when a greater number was attempted, the added series of impulses seemed to fill the gaps in the other series and produce practically a continuous current, causing serious interference between the messages. The need of a better form of an electric wave was apparent; making and breaking the circuit so many times a second seemed but the first step in the development of his idea. The fact is, Bell had had for a year or more a clear conception of the sort of current he needed, one undulating in waves which would be the exact equivalent of sound vibrations, although he had as yet devised no satisfactory means of producing such a current. An electric current undulating in true wave form would not, he believed, smooth out into a continuous current when several series of impulses were superposed but would keep its wave form through all the complexities that might be impressed upon it. Many sounds can traverse the same air without confusion, so, he thought, such a system of electric waves having the mathe-

matical form of sound waves in the air, might transmit an indefinite number of pitch series on a single wire, to be selected and resolved into separate messages by his tuned receivers.

Bell also foresaw that the apparatus which could generate and transmit such true electric waves might also solve another great problem he had been dreaming about.

One must imagine a world in which the telephone was absolutely unknown to appreciate my feelings when one evening during the course of some experiments on his telegraph apparatus, Bell told me he had an idea by which he believed it would soon be possible to talk by telegraph. He put his conception into the words of his famous formula which I then heard for the first time: "If," he said, "I could make a current of electricity vary in its intensity, precisely as the air varies in density during the production of a sound, I should be able to transmit speech telegraphically." Some practical mechanism to produce such a current was the goal to be striven for, he asserted. He then described to me what he called his "harp telephone," a complex affair having an elongated electromagnet with a multiplicity of steel reeds tuned to many pitches and arranged to vibrate in proximity to its poles; as if the magnets of a hundred of these receivers were fused together side by side. These reeds might be considered as analagous to the rods in the harp of Corti in the human ear. It was Bell's first conception of a speaking telephone. His idea was that a sound uttered near the reeds would cause to vibrate those reeds corresponding to both the fundamental tone and to the overtones of that sound. Each reed would generate in the magnet an electric wave all of which would combine into a resultant complex wave. This passing through a similar instrument at a distant station would, he imagined, set the same reeds into motion and so reproduce the original sound. He had even considered the possibility of using a single reed actuated by a parchment diaphragm over an ordinary electromagnet. He had not had either of his conceptions constructed for he was sure that electric waves generated in this way would be too feeble, to be of the least practical value. His harp telephone, however, was a favorite idea with him and he often spoke of it to me. It was never constructed probably on account of the expense, but with this clear conception in his mind, of the possibilities of a true electric wave, struggling for practical expression, Bell continued his work on his harmonic telegraph

trying to attain a result clearly impossible with a transmitter that merely made and broke the circuit.

I am afraid that my attitude towards Bell's telegraph, after several months' work on it, had become one of disgust with its perversities, and hopelessness as to its future. Its operation was so uncertain and baffling that I remember that even Prof. Bell himself began to lose his enthusiasm. His confidence in the intermittent current was vanishing and means for generating his better waves had not arrived. But, " when half gods go, the gods arrive," and this time of depression and disappointment was the right preparation for the new development that was close at hand.

In the attic of the building 109 Court street, Boston, where Williams's shop was, two rooms had been partitioned off and used by Williams for the manufacture of tin foil condensers. These rooms Bell used as his laboratory at that time. Those rough attic rooms, freezing in winter and unbearably hot in summer, had witnessed many discouraging experiments with the harmonic telegraph with a few slight successes, but on the afternoon of June 2d, 1875, something came to light there that certainly was a recompense for all previous troubles. A slight derangement in the telegraph apparatus gave an opportunity for the great idea that had been incubating in Bell's mind so long to break through its shell.

On that afternoon Bell was in one of the rooms tuning the receivers, an operation they constantly needed. He had a novel way of doing this that he had originated and which had become a habit with him. When he was trying to bring the pitch of a receiver reed into accord with that of its transmitter, he would press that receiver reed against his ear. He could then hear the nasal drone of the intermittent current coming from the transmitter in the other room and by changing the length of the receiver reed he could adjust its pitch to correspond with that tone. It is interesting to note that when one of his harmonic receivers is used in this way, it becomes a close analogue of a modern telephone receiver, as the edges of the ear clamp the free end of the spring and so damp its natural rate of vibration and cause it to vibrate as a diaphragm.

On the afternoon of June 2d, 1875, Bell was doing this with one of the receivers and at that very moment I happened to snap the steel reed of another instrument in the other room connected into the same circuit, which for some reason was

not vibrating as it should, and needed that physical stimulus to start it. It did not start at once so I gave it several vigorous plucks, undoubtedly expressing my opinion of the thing in vivid shop language, when I heard a commotion in the next room and out Bell came in great excitement to see what I had been doing, telling me that he had heard in the receiver at his ear the unmistakable timbre of the sound of one of the reeds. His excitement came from his realization that he had heard the first real sound that had ever been transmitted electrically. It needed but a slight examination of the apparatus to reveal the fact that the steel reed I had snapped, magnetized by its long use in connection with magnets, was functioning as a magneto-electric generator and by its vibration had generated in its magnet an electric current that was moulded into undulations exactly analogous to the sound waves of the plucked reed. That such slight means could generate a current not only strong enough to be heard in the receiver but actually to set into visible vibration the reed of another receiver in the same circuit in Bell's room, was a revelation to him. He saw at once that he had been wrong in thinking that the vibration of a steel reed could not produce electric waves of any practical value and that here was the solution, not only of his harmonic telegraph but also of his speaking telephone. He realized immediately that the apparatus that could generate, transmit and receive so efficiently one sound with its fundamental tone and with its overtones could undoubtedly be made to do the same for any sound, even speech itself. The gods had arrived, bringing new enthusiasm and hope; even my gloom was dispelled. We spent the rest of the day repeating the experiment by snapping many different sizes and shapes of steel springs and tuning forks over magnets with the same surprising result and before we parted that night Bell gave me directions for constructing the first speaking telephone. He knew that the diaphragm of the Scott phonautograph when impelled by the vibrations of sound would impress them on the recording style attached to it; why then would not such a diaphragm actuated by the voice, force the steel reed of one of his receivers to follow the vocal vibrations and cause it to generate electric waves with the form of speech waves? Following this thought to its conclusion, Bell sketched out the first speaking telephone the world has ever seen and gave me directions for its construction. I was to mount one of the harmonic receivers in a wooden

frame, attach the free end of its spring to the center of a tightly stretched parchment drum head, also mounted in the framework, and provide a mouthpiece to concentrate the voice on the other side of the drum head.

I did this the next day. Here is a replica of it. All that is left of the original is now in the National Museum at Washington. My recollection is that I had this first telephone ready for testing the next day, June 3d. It had many defects. The diaphragm was delicate and easily torn and as it absorbed the moisture of the breath required constant tightening, but it transmitted to my ear over a wire about 200 feet long, running from the fifth story of Williams's building to my work bench on the third story, the unmistakable timbre of Prof. Bell's voice in a few imperfect words, using for listening one of the harmonic telegraph receivers through which Bell had made the discovery. It was a meagre result and a bitter disappointment, for I, at least, and, I fancy, Prof. Bell too, had anticipated a much greater conversational fluency even in that first telephone.

I have noticed that one's mental attitude towards a phenomenon changes as the novelty wears off. The new effect does not seem so wonderful after a few repetitions. This is perhaps the reason why my memory tells me that during the months immediately following the discovery that magneto-electric waves generated by a vibrating steel reed were strong enough for practical use, the telephone seemed to grow poorer in its operation instead of better. Bell carried on many experiments for which I made the apparatus, with the purpose of increasing the strength of the new wave not only for its use in his telegraph but also in his telephone. He felt that any improvement applicable to one invention would also help the other. His work for some months was devoted to the telegraph as well as to the telephone, for his friends and financial backers were all strongly of the opinion that it was much wiser for him to devote himself to a real practical thing like the telegraph rather than to such a chimera as the telephone.

Progress was over the same desert road with a few green spots that inventions seem prone to travel on and it was not until March 10th, 1876, nearly ten months after its birthday that the telephone transmitted its first complete sentence. Though not so noble as the first sentence that Morse telegraphed from Washington to Baltimore a few decades before, "What hath God wrought," still the telephone's first sentence had a

certain homely practicality about it that clearly takes it out of the category of the frivolous. It was, "Watson, come here, I want you," uttered by Bell from his laboratory to his bed room in the boarding house, number 5, Exeter Place, Boston. I am sure that I went at once. Commonplace as it was, the sentence seemed to break the spell and the telephone progressed after that by leaps and bounds.

I have here the wire over which that first sentence was sent. With a forethought that quite surprises me today, I took down this wire when the laboratory was vacated in 1877, inscribed it and put it into a safe where it remained until a year or two ago when I presented it to the American Telephone and Telegraph Co. for its museum. The inscription, which I wrote when I first took it down, is as follows: "This wire connected room 13 with room 15 at number 5 Exeter Place, Boston, and is the wire that was used in all the experiments by which the telephone was developed from the fall of 1875 to the summer of 1877, at which time the telephone had been perfected for practical use. Taken down June 8th, 1877, by Thomas A. Watson."

This was the year of the Centennial Exposition at Philadelphia and Bell decided to make an exhibit there of his inventions. He had me make for him some nicely finished telephones of the best forms that he had devised, including his first battery transmitter.

In June, 1876, Sir William Thomson, chairman of the committee on the electrical exhibits, with members of his committee, examined and tested Bell's apparatus. We have a valuable record of the impression the telephone made upon his mind in his opening address to the British Association, September 14th, 1876, wherein he said:

I heard, "To be or not to be * * * * there's the rub," through an electric telegraph wire; but, scorning, monosyllables, the electric articulation rose to higher flights, and gave me messages taken at random from the New York newspapers—"S.S. Cox has arrived" (I failed to make out the S. S. Cox) "The City of New York," "Senator Morton," "The Senate has resolved to print a thousand extra copies;" "The Americans in London have resolved to celebrate the coming 4th of July." All this my own ears heard, spoken to me with unmistakable distinctness by the thin circular disk armature of just such another little electromagnet as this which I hold in my hand. The words were shouted with a clear and loud voice by my colleague judge, Professor Watson, at the far end of the tele-

graph wire, holding his mouth close to a stretched membrane, such as you see before you here, carrying a little piece of soft iron, which was thus made to perform in the neighborhood of an electromagnet in circuit with the line, motions proportional to the sonorific motions of the air. This, the greatest by far of all the marvels of the electric telegraph, is due to a young countryman of our own, Mr. Graham Bell, of Edinburgh, Montreal, and Boston, now becoming a naturalized citizen of the United States. Who can but admire the hardihood of invention which devised such very slight means to realize the mathematical conception that, if electricity is to convey all the delicacies of quality which distinguish articulate speech, the strength of its current must vary continuously and as nearly as may be in simple proportion to the velocity of a particle of air engaged in constituting the sound?

Up to the summer of 1876 all the tests of the telephone had been made on indoor wires but soon after this convincing trial at Philadelphia, it became evident to Prof. Bell that his invention was ready for higher flights. Some preliminary tests on a real line in Brandford, Canada, in which the transmission was all in one direction, the return communication being by telegraph, were followed by a complete test of the telephone's practicability as a transmitter of intelligence between distant points under outdoor conditions. On October 9th, 1876, Bell and I carried on a long conversation over a real telegraph wire about two miles long running from Boston to Cambridge, Mass. Bell was at the Boston end, I, at Cambridge. The telephones we used were those that Bell had exhibited at Philadelphia and were probably the identical instruments with which Sir William Thomson made his famous tests. In order to prove to a doubting world that the telephone could be accurate in its transmission, we made a record of that first conversation ever carried on over a real line and so it has been preserved. At the beginning of the test we were not able to make our voices audible to each other. The cause seemed to be the high resistance of a telegraph relay that I discovered in the circuit in another room in the Cambridge factory, for, after I cut that out, we were able to talk with the greatest ease, as the opening sentences of our recorded conversation indicate, which were:

"Bell: What do you think was the matter with the instruments?
Watson: There was nothing the matter with them.
Bell: I think we were both speaking at the same time.
Watson: Can you understand anything I say?
Bell: Yes, I understand everything you say.

Watson: The reason why you did not hear at first was because there was a relay in the circuit.

Bell: You may be right, but I found the magnet of my telephone touching the membrane.

Watson: I cut this relay out, and then the sounds came perfectly.

Bell: I hear every syllable. Try something in an ordinary conversational voice.

Watson: I am now talking in quite a low tone of voice.

Bell: The sounds are quite as loud as before and twice as distinct"—

and so on for more than a hour. This record which was published in the *Boston Advertiser* of the next day shows a surprising accuracy when the crudeness of those early telephones is taken into consideration.

I need go no further in my account of those days of struggle. The successful working out of the telephone, as in the case with all inventions, was a matter of endlessly considered detail. It was patient, plodding work with a few hours of intense excitement. Other tests were made later in 1876 on still longer lines, and in April, 1877, the first telephone line was constructed, 4 miles long, and the telephone installed thereon, beginning its competition with the telegraph as a practical business proposition.

Since then, what tremendous things have been done by the telephone engineers on whom the responsibility has fallen, of continuing the work so splendidly inaugurated by Dr. Bell. The work of these men during the 38 years that has elapsed since Dr. Bell's experiments on the telephone has been ceaseless, energetic, untiring, wise, and accurate in the highest degree. Telephone engineers have overcome one by one the multitude of obstacles that stood in the way of that high ideal—universal service, until today we applaud the latest achievement, under the able leadership of your incoming President—transcontinental telephony, the marvel of which has impressed itself deeply upon my mind all the more because Dr. Bell and I had the honor of formally opening the New York-San Francisco telephone line on January 25th of this year, as we opened the first telephone line, 2 miles long, between Boston and Cambridge, 39 years before. We talked over this line 3400 miles long (really 4400 miles, for its terminus was, during the most of the time, in Jekyl Island, Georgia) more clearly than we talked from Boston to Cambridge 39 years before. Amazing

as this was, a climax of the wonders I had been participating in was reached when Dr. Bell switched in another telephone and said to me through it: "Mr. Watson, I am now talking through an exact duplicate of the first telephone made in 1875. Can you hear me?" I heard him perfectly, and when I explained to the audience at my end of the line just what was happening and repeated Dr. Bell's words, I was not surprised to see tears in the eyes of several of those hard-headed business men of California, for I myself was thrilled through and through with the thought of the immensity of the work that had been done since I made that first telephone for Prof. Bell and with my realization that this transcontinental line, stupendous achievement as it is, was merely a big incident in the life of the men whose brains have built up an organization almost incomprehensible in its size and scope, with its nine million telephone stations, making twenty-eight million telephone conversations each day over twenty million miles of telephone wires—that stupendous organization we call the "Bell system."

Even these figures are but part of the whole, for there are now in the world more than 14 million telephone stations, making 42 million conversations daily over 33 million miles of wire. We can but wonder at such a fructification in four decades of that virile conception of the man we today honor ourselves by honoring—Alexander Graham Bell.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 16, 1915.

STANDARD MARINE ELECTRICAL INSTALLATIONS

BY H. A. HORNOR

ABSTRACT OF PAPER

The requirements of merchant and naval installations are cited in brief. The rules of the classification societies are reviewed and present practise is fully discussed. Then follows the specific applications to a number of different types of ships including both merchant and naval vessels. The reasons for the application of electric propulsion to a battleship are briefly given.

THE ESTABLISHMENT by the Institute of a Committee on the "Use of Electricity in Marine Work" has been fully justified in that already a number of papers on specific equipments such as, Electric Steering Gear, Gyroscopic Compass, Electric Heating, Searchlights, Electric Propulsion, etc., have been presented, discussed and recorded. There is here a two-fold value the segregation for reference and research by those concerned in this work, and the increased value to the Institute as its part in the development of what presages to be one of the important applications of electricity. This Committee having collected data on all the important points connected with marine electrical installations from as many different sources as possible desires to present a monograph recording the best practise at this time in this country.

The rules and requirement for merchant vessels will be first treated; next will follow the general considerations for government vessels; and then a brief consideration of the applications to a number of different types of vessels.

GENERAL REQUIREMENTS FOR MERCHANT PRACTISE

Merchant vessels are usually constructed in accordance with the requirements of some classification society which establishes also the rules for the electrical equipment. In this country most of the vessels are built to the requirements of either the American Bureau of Shipping or Lloyd's Register of British and Foreign Shipping. Other classification societies are Bureau Veritas (French), Germanischer Lloyd (German), British Cor-

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poration (English), and Great Lakes Register (U. S. A.) Besides the rules of these underwriting societies the electrical installation must conform to the rules of the Steamboat Inspection Service, under the cognizance of the Department of Commerce, in certain cases to the rules of the National Board of Fire Underwriters, and also to certain specifications issued by the owners of the vessels. The rules of the societies above mentioned and those of the government are general in character and apply to all classes of vessels. The requirements of the owners are usually specific and serve to standardize for them the various equipments so as to reduce upkeep and maintain a similarity of spare parts. It frequently happens that the owner specializes in a certain trade and his vessels are therefore built and equipped for this definite purpose.

The requirements of the American Bureau of Shipping for the electric plant are briefly as follows: The voltage shall be about 125 volts preferably direct current. If alternating currents are used there must be an increase of 50 per cent in the insulation resistance of the wires. Generators must be insulated by mounting them on dry wood or other equivalent insulation. The same requirement applies to motors. No single wire larger than No. 12 A. W. G. is allowed, and no single solid wire smaller than No. 14 A. W. G. except in fixture wiring. Both conduit and wooden moulding for the protection of the conductors are allowed but conduit is preferred throughout. A heavier insulating covering is required for conductors led through unlined conduits. Slate or marble switch boards are required, equipped with necessary instruments, cut-outs, knife switches, etc. When the wires are carried through the steel structure they must be led through metallic conduits or protected by hard rubber or equivalent bushing. Twin wire is not permitted in conduit if the circuit passes through the fire rooms or other hot places in the ship. Stuffing tubes are required wherever the conduit passes through a deck or water-tight bulkhead. All joints and splices are protected by water-tight junction boxes. Cut-outs, as much as possible, to be limited to centers of distribution but are allowed on mains if properly protected by a water-tight box. No circuit requiring more than six amperes must be dependent upon one cut-out. Where exposed to moisture, lamps must be provided with a vapor-proof globe, and for mechanical protection, a guard. Although portable desk lamps are permitted, lights must not

be suspended with flexible conductors. Signal lights must be on a separate circuit and controlled in the pilot-house from a tell-tale board which indicates a defect in the lamp or circuit. All leads to seachlights must run directly from the switchboard to a switch near the searchlight. Arc lamps are permitted but must be protected by cut-out and switch and from mechanical injury. To prevent the effect of electric currents on the adjustment of the magnetic compasses both polarities must be carried in the circuit.

The American Bureau of Shipping make the following special requirements for oil tank vessels: Electric lighting only to be used. Single-wire system not permitted. Special designs of fixtures and appliances must be made if permanent lights are used in any spaces subject to vapor or gas. If wires are run in such spaces their insulation must be unaffected by oil or oil fumes. Generating sets in duplicate are required and all wires must be encased in conduit.

The rules of Lloyd's Register differ slightly from the American Bureau and only the important differences will be noted. No preference is stated as to kind of current or the amount of voltage. "Double pole" fuses are not permitted when the voltage exceeds 125 volts. Permission is granted in addition to the use of wooden mouldings, and conduit, for the employment of steel-armored conductors secured by screwed clips. Cables exposed to the weather or moisture must be lead-covered as well as steel-armored. As in the use of conduit, stuffing tubes must be provided at water-tight bulkheads and decks. The switches on main switchboard must be of the quick-break design. The signal lights must be controlled from a point accessible to the officer of the watch but a tell-tale indicator is not required. Special rules are given covering the single-wire system but American practise is entirely committed to the two-wire system. Single-wire system is not permitted on oil tank vessels. All wires in spaces subject to petroleum vapor or gas to be lead-covered or the insulation to be unaffected by petroleum. No joint, switches, or fuses, are allowed to be located in the pump rooms of oil tank vessels. Wires to lamps to be carried to the pump room from distribution junction box placed outside. Compasses should be adjusted with and without the generators running.

It is to be noted that the classification societies make no rules governing the installation of interior or exterior signalling systems.

The rules of the Steamboat Inspection Service do not relate to the intimate points of installation or equipment but rather to the provision of appliances for protection to the vessel, her passengers, cargo, and crew. Vessels using a gong signal must have a tube returning to the pilot-house so that the signal when given in the engine room may be heard at the same instant in the pilot-house. This is usually an additional precaution on large vessels in case of derangement of the mechanical or electrical telegraph which must be arranged to repea t the signals between the pilot-house and the engine room. "On all steamers where the distance is more than 150 feet between perpendiculars of pilot-house and forward part of the engine room " a telephone must be installed in lieu of a speaking tube. Vessels which do not keep watchmen on guard day and night in the sleeping accommodations must equip such quarters with alarm bells which can be energized at will from the bridge or pilot-house. No lights are allowed on the outside of the structure of the cabins or hull that will interfere with distinguishing the regulation signal lights. Passenger-carrying steamers lighted by electricity, and whose dynamos are located below the deep-load line, must carry an auxiliary lighting system above the deep-load line. This auxiliary lighting system must be sufficient to allow the passengers and crew to readily find their way to the exist. On account of this latter provision vessels are permitted to carry gasoline to the amount necessary to provide for such auxiliary lighting and wireless system. These regulations further provide for the type and location of the signal lights—port, starboard, masthead, range, and stern—and such lights that should be displayed when the vessel is at anchor, aground, etc. A prolonged fog-whistle must be blown at intervals of every two minutes by a vessel under way and two prolonged blasts every two minutes when not under way. When towing another vessel, or being towed, a prolonged blast followed by two short blasts must be sounded.

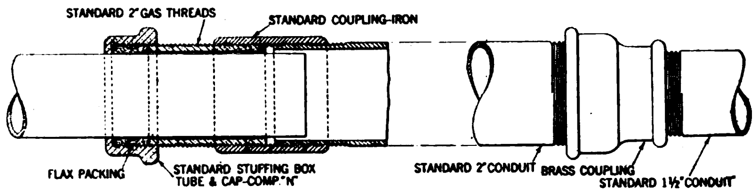
Voice tube must be installed between pilot-house and wireless station.

The rules of the National Board of Fire Underwriters are now in the process of revision for which purpose many conferences were held with the Marine Committee of the Institute. There are a few vessels which ply inland waters that come under the jurisdiction of the Fire Underwriters, as will be noted later, and it is but natural that their rules will coincide with those of the classification societies and established marine practise.

From the foregoing it will be seen that the owner, for general methods of installation, needs only to state that the electrical installation must conform to the rules of the classification society. The owner then specifies what the requirements of his service are, namely, the number and size of the generating sets, the number of searchlights, incandescent lamps, motors, etc. etc. Special signaling devices other than those required by law are often necessary for the convenience of the officers, passengers, and crew. The owners specifications are a guide for estimating the cost and accomplishing a formal contract.

Merchant Marine Practise

In general, the commercial installations in this country combine wooden mouldings and iron conduit. The manufacture of steel-armored lead-covered wires was started in this country about four or five years ago and was recently adopted by the



Slip Joint for Conduit—Merchant Marine—Type 1

Navy. It is usual to find that one practise influences the other, so that now the use of steel-armored conductors in merchant practise is increasing.

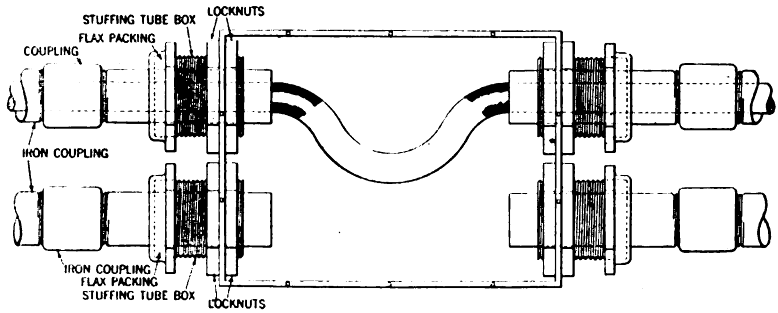
For vessels designed with the propelling machinery aft, requiring long leads to the amidships and forward compartments, it is necessary to provide a sliding connection for the conduit and a loop box for pulling in the wire. This is necessitated by the expansion and contraction or working of the structural parts of the vessel. Two designs of such appliances are shown in the illustrations. Oil tankers are so arranged that the electric leads must be carried under the walking bridge which connects the bridge house just forward of amidships and the after house; and slip joints are requisite in this type of conduit installation.

Except for very close work all conduits are bent cold, and with the exception of the termination of a lead, elbows are not permitted. The restriction of fittings of all kinds is deemed

advisable. For the purpose of overhauling and to facilitate the safe installation of the cables it is necessary to use, especially at bends, couplings, but these must not be right and left threaded. All conduit connections should be made up with white or red lead used generously to aid inspection.

It is recommended that splicing of wires larger than No. 12 B. & S. be not permitted and it is further suggested that even such small joints be made with a soldered sleeve. On the other hand care must be exercised in the use of mechanical joints as the working of the vessel may cause the connection to loosen allowing "grounds," "opens," or "short circuits." This is not merely a matter of design and material but one of good workmanship and careful inspection.

The distribution of energy as above noted is made on a two-



Brass Loop Box and Slip Joint for Conduit—Merchant Marine—Type 2

wire metallic system. Copper of the highest conductivity is used for all wires and the insulation is equal to and often greater than the requirements of the classification society. The opinion has been expressed that it may be preferable to reduce the required thickness of insulation and make the material of better quality. The well-advised owner in preparing his specifications should see to it that the type of manufacture be clearly stated. Feeders are led from the main switchboard to centers of distribution, and from thence branch leads, not carrying, except in special cases, more than 660 watts. When conditions of the ship's structure or arrangement will not facilitate this method of distribution, the feeders are broken by special feeder boxes of water-tight construction, mains taken off and branches in turn taken directly from the mains. For the lighting system

an allowable voltage drop of 3 per cent from the main switchboard to the farthest light, and for power 5 to 8 per cent, is considered good practise. A potential of 110 volts is generally adopted in accordance with the standard incandescent lamp. Due to the disagreeable effect and confusion to passengers it has been suggested that every compartment for passenger accommodation should be supplied with light from more than one main feeder. This would not apply on a freight steamer as the crew are not so affected. Putting aside the use of fixture wire, and using No. 14 B. & S. wire for branch circuits, the permissible watts should be based on the voltage of the system times the carrying capacity of the wire. In this case as No. 14 wire carries safely 12 amperes the permissible watts on 110 volts would be 1500.

Generating sets are designed so that the prime mover and generator are direct-connected and mounted on a common bedplate. As will be noticed subsequently in small vessels and freight steamers where the sets are of small capacity—say from 2 kw. to 20 kw.—the prime mover is a reciprocating engine. This unit possesses distinct advantages of operation from the practical side, as such ships cannot carry an engineer expressly for the care of the generating plant. The chief engineer of such vessels must be well skilled as regards reciprocating engines as these are his means of propulsion, but the generating sets must operate with great reliability to satisfy this service. The manufacturers today have designed sets with forced lubrication and a combination of both forced lubrication and gravity feed so that these sets function ordinarily without much attention. There are three points of importance from a mechanical standpoint regarding generating sets, namely, ample reinforcement of the ship structure to form a foundation for the set. The builders' designers do not all agree as to the proper foundation and in some cases the generators are bolted directly to the deck or platform, in other cases a wooden base is provided on top of the deck and again still others believe in building up a steel structural foundation on top of the deck and not bolting down the set until the vessel is nearly completed. Next, these sets must be able to operate either condensing or non-condensing with approximately 8 to 10 pounds back pressure. They must exhaust either into the feed water heater, or the main or auxiliary condenser, or to the atmosphere. It is probable, because they are usually exhausted into

the feed water heater for steam economy, that greater stress is not laid upon the efficiency of the prime mover. The third point is that for installation on shipboard the steam connections must be flanged so as to reduce the number of joints in the pipings and because of the vibration set up in the vessel when the main engines are working.

Small direct-connected turbine generating sets have been employed on shipboard and in certain installations have given satisfaction but opinion among owners differs as to the advantages of the turbine over the reciprocating engine. Many marine engineers object to the high rotative speeds for direct-current generators and the lack of economy unless a high vacuum can be provided. On the other hand some engineers prefer the turbine drive because of the reduction of upkeep and ease of operation.

The use of reduction gears between the turbine and generator is now being suggested. In this set the water rate will doubtless be greatly reduced, approximately 10 per cent, and the speed of the generator can be brought down to reasonable limits with high speed on turbine. Although such sets have been installed no service data are available for comparison or comment. These sets, however, have shown as expected a great reduction in weight and water rate.

The generator is usually compound-wound and in the larger sizes provided with commutating poles. Special precautions are taken so that oil cannot creep along the armature shaft and that the non-corrosive parts are furnished. A hand rail or guard is mounted around the generator set, in order that no one may be thrown against the set when the vessel is pitching or rolling.

The material for switchboards has up to the present time been slate and in rare cases marble, but as will be seen later, naval practise has turned to a special composition. This may shortly change the merchant practise. Ordinarily the circuits are arranged for the parallel operation of the generator, if there be more than one. Certain owners prefer separate operation, however, and then double bus-bars are provided with throw over switches. Marine switchboards must be built as compactly as possible, so that they may be mounted near a bulkhead As was noted above, Lloyds' rules require quick-break switches even on 110 volt systems, and it is recommended that two springs be required for each blade. The bus-bars though mounted on

insulation are bare copper strips and opinions do not concur as to the advisability of insulating the entire bus-bar. The usual instruments are mounted on the face of the board and inclosed cartridge fuses are installed on both sides of the circuit. Although it is a matter of expense, on switchboards handling 200 amperes or over from the main leads of the generating set, double arm circuit-breakers are provided instead of fused lever knife switches. The refillable fuse of proper design is now being introduced but proper precaution must be observed to prevent unauthorized metals replacing the original.

On vessels of 4000 tons burden or over, the searchlight should not be less than 18 inches in diameter. The searchlight feeder is run direct from the main switchboard to a fused knife switch located usually in the pilot house near the controller of the searchlight. A variable external resistance is placed in series with the arc for proper adjustment. This is a steadying resistance as the arc burns better when the constant potential circuit is as high as 80 volts or higher. Opinions differ as to the location of this resistance as much heat must be dissipated in order to make this reduction of voltage with relatively high current. In some cases the resistance is located near the switchboard and in others it is preferred near the searchlight in the pilot-house. Up to the present time the lamp mechanism has been that of magnets operating through a ratchet on a screw, permitting both hand and automatic operation; but the naval projector lamp is now operated by a small motor and it may be assumed that such will shortly come into merchant practise. For adjusting the arc voltage arrangements are provided on the main switchboard. To insure against inductive disturbances from the wireless telegraph, the exposed leads of the searchlight must be carefully encased in an iron shield or wrapped with iron wire. This protective covering must be well grounded to the hull of the vessel.

The use of iron branch junction boxes and iron steam-tight globe fixtures meets with general approval, and the use of brass or bronze is looked upon as a refinement and expense. One opinion in this matter is interesting "it discourages theft, a source of great annoyance to ship owners from stewards, stevedores, etc." It is the consensus of opinion that the guard on steam-tight fixtures is in most cases unnecessary and superfluous. In cargo spaces, especially on coastwise vessels shipping package freight, the fixtures are protected by steel strips placed

from beam to beam. There seems no reason why cheaper metals should not be used in the ornamental fixtures. The use of the heavier metals or alloys is a matter of taste and expense. Foreign passenger vessels have for sometime been using majolica or beleek fixtures which add to cleanliness, are substantial, are more readily insulated and do not require refinishing. Two passenger vessels recently built in this country for the Great Northern Pacific S.S. Co. were so equipped. The small lighting unit unshielded is generally employed although the large unit lends itself for the general lighting of large cargo spaces, and the machinery spaces. The employment of indirect or semi-indirect units is very small. This is attributed to the low deck height and the usual exposure of the deck beams. It is also thought that enough attention has not been paid to the proper illumination of passenger accommodations, because of the general feeling of ship owners that the passengers prefer to spend their time mostly on deck. The large advance in better lighting seen on some of the latest ocean liners does not confirm this opinion for a service where the passengers may be better cared for inside the vessel during rough voyages. Tungsten filament incandescent lamps are largely used outside of the machinery spaces. In these spaces the vibration is such as to require the carbon filament lamp.* Units of 250-watt tungsten, with proper reflector, have now superseded the arc lamp for the general lighting of the machinery spaces. Cargo reflectors containing four small lamps are still used as portable units for lighting such spaces, as well as for gangway lighting. The tendency is toward great lightness for hand portable units, and a reduction in the number required to be water-tight. The water-tight fixtures add so much weight that the lamp is too unwieldy compared to the non-water-tight. A simple light wire guard to protect the incandescent bulb is deemed sufficient. The navy standard switch, and switch and receptacle are generally used on merchant vessels. There has been but one good receptacle and plug designed for water-tight work outside of the navy design and this device is very expensive. Its use, however, has proved of great advantage. The practise in this country still adheres to the Edison screw socket but it would seem that improvement must come along this line. Its general adoption is evidently caused by land commercial prac-

*There have been some successful installations of tungsten lamps in machinery spaces.

tise but unquestionably a design on the lines of the Edi-swan or bayonet type should prove more satisfactory.

Ordinary land motors are installed but it would be unwise to continue this practise if the use of motors increases, as the upkeep to the owner would be such that the application would soon be discouraged. Motors should be designed so as to prevent oil from creeping along the armature shaft, a tendency when the ship rolls or pitches. Easy means for overhauling and the use of non-corrosive parts are essential. It seems that the owners of vessels in this country are overlooking the advantages of economy in the lack of a more extended use of electric power. The question of first cost is easily counterbalanced by the reduction in upkeep, ease and readiness of service provided by the electric motor. Many of the applications have been long tried in naval service and the apparatus is not of an experimental nature. The controlling devices for motors are similar to those of land practise except that where exposed to the weather and located in the machinery spaces, water-tight protecting boxes are supplied. To prevent unauthorized handling, non-water-tight sheet metal inclosing cases with padlock are provided in all cases.

Besides those systems of communication which are required by law the owner finds many adapted to the convenience of passengers and crew. Such systems should be energized preferably by a low voltage (20 volts) if used by passengers. The general opinion is that only direct current should be used. Many attempts have been made to utilize ordinary land telephones on ship-board but they do not seem to give the service desired. Special marine telephones are now being installed and carefully watched. A combined system of loud speaking telephones between the bridge and engine room and flat speaking for inter-communicating purposes appears to have some merit. The telephones for the bridge and engine room are made entirely water-tight and provided with double receivers of the watch case pattern. All the telephones are made portable and of the hand microphone type as experience has shown that the human body performs the function of a cushion to the ship's vibration better than any other device. Electric telegraphs for transmitting orders, from the bridge to the engine room, for sending docking orders, etc., etc., are often installed on merchant vessels, but it is recommended that such instruments when needed should preferably be of the lamp type. The

electrically operated valve for the main steam whistle in addition to the mechanical hand pull is now frequently installed, even on freight vessels, and the clock mechanism is arranged with two contact disks so that the vessel may comply with the law when towing or being towed. In all such applications the object most sought after is simplicity and reliability—the functioning without attention.

Fire alarm systems are very rarely installed on freight vessels but passenger vessels are always so equipped. The older systems have not proved of great value but two systems are now on the market; one applicable to cargo carrying vessels by means of which not only is the location indicated by smoke coming from the compartment but also admits live steam to the seat of the fire. This requires an expensive system of piping which is not always satisfactory. The other system operates on the principle of the expansion of air due to a rise in temperature. A pipe of very small inside and outside diameter (so small that it can hardly be seen when exposed on the decks or bulkheads) is installed in all the compartments. This pipe may be placed on the trim or cornice and is very unobtrusive. A fire may in this way be detected while in the early stages and large areas easily and economically protected. The indicating devices can be located in two or more places and, as is frequently done, can be made to resemble the deck plans of the ship. The indications are given by the lighting of a small battery lamp and the sounding of an alarm.

An increasing number of coastwise vessels now carry a submarine receiving set. This consists of two tanks filled with brine located in a lower forward hold of the vessel. Transmitters similar to telephone transmitters connect with double receivers located in the pilot-house—one receiver connecting to the port tank and the other to the starboard. The submarine bells located on the lightships or buoys along the coast may be heard through the water by this means and the direction in case of fog or thick weather detected by noting the equality or inequality of the strength of the signal on each tank. The vessel may also swing around to enable a bearing to be sufficiently assured so that danger may be averted. The device has been reported as operating satisfactorily and this is attested to by the increase in the number of vessels so equipped.

Although wireless equipments are required by law on passenger vessels many freight vessels carry such equipment. The

advances in this field are exceedingly rapid and therefore no set, as described, could be looked upon as a standard but it would seem desirable to give some idea of this apparatus. A typical installation for freight vessels consists of the following parts: A motor generator supplied with energy from the 110 volt direct current system. The motor and generator armatures are on the same shaft. The a-c. generator has a speed of 2400 rev. per min.; it has 12 poles and it generates a voltage of 500 at 240 cycles. The synchronous gap, which is a disk of composition insulation and carries a stud for each pole of the generator, is mounted on the generator end of the shaft.

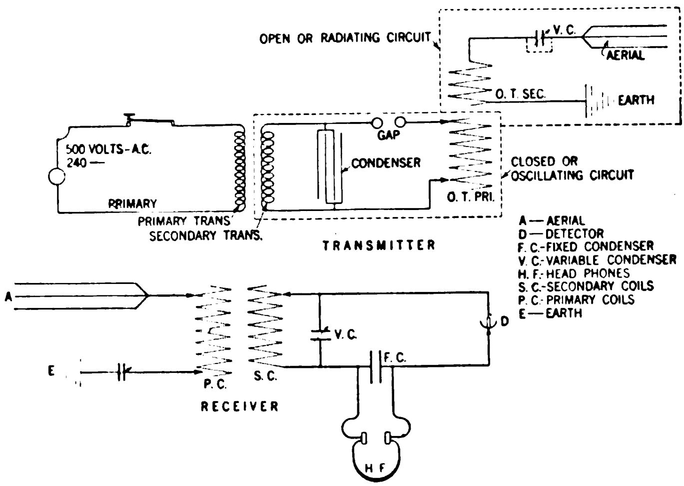


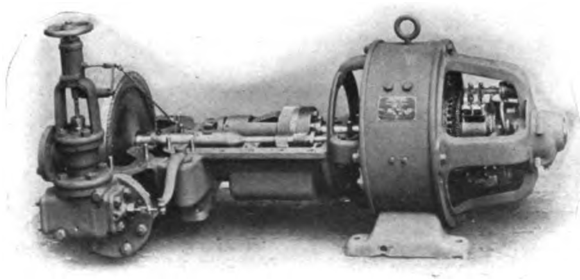
DIAGRAM OF CONNECTIONS FOR WIRELESS TELEGRAPH—MERCHANT TYPE

Two stationary studs are secured on the disk muffling box and the spark discharge takes place between them. When these studs are adjusted to synchronism, the spark discharge occurs only when the a-c. voltage reaches its peak of alternation thus allowing only one spark discharge for each alternation or 480 sparks per second. In this manner a pure musical note is produced, slightly lower in tone than the E string of the violin. The transformer steps up the 500 alternating volts to 12,000 and charges the condenser. This condenser is made of high quality glass plates coated with copper or tinfoil and immersed in oil (flash point 300). It is used in series parallel banks and forces the energy received into the rotary gap and

oscillation transformer. The primary of the oscillation transformer is connected in series with the gap and condenser. The primary coil carries a movable contact and by varying this contact on the turns of the coil, the wave length may be adjusted. The energy is transferred from the primary coil of the oscillation transformer to the secondary coil (which is several inches from the primary coil) by magnetic induction. The secondary coil of the oscillation transformer is connected to the aerial in the following manner: One terminal goes to the earth, the other through inductance coil for lengthening aerial period or wave, and condenser in series for shortening wave. The spark gap, oscillation transformer primary, and primary condenser, make up the "closed circuit" or "oscillating circuit." The oscillation transformer secondary, the aerial inductance and condenser, the aerial and earth, form the "open circuit" or "radiating circuit." The "closed circuit" wave and the "open circuit" wave must be in resonance before the "open circuit" willl radiate energy on the aerial. A hot wire ammeter will show a maximum reading when the two circuits are balanced. The aerial consists of seven strands of No. 18 silicon bronze hard-drawn wire used to prevent sagging or stretching. Wires are spaced on a 25 foot spruce spreader and insulated from spreader and ropes by four feet of hard rubber rods. The receiver consists of the tuner for tuning to resonance all incoming waves by variable inductances and capacities. In this manner waves of different lengths and frequency may be selected. The detector is of the carborundum crystal type mounted on the tuner and rectifies the signals to be heard on the diaphragm of the head telephone. These telephone receivers are extremely sensitive, having a resistance of 3000 ohms. This set establishes reliable communication under favorable conditions at a distance of 3000 to 4000 miles.

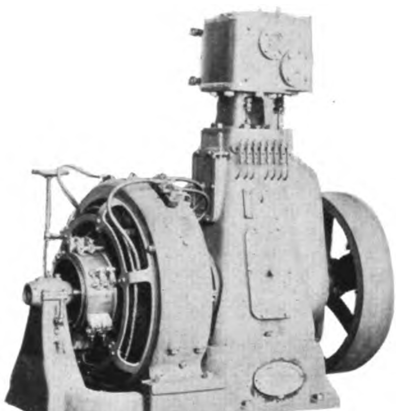
Naval Practise

The requirements of the navy constitute naval practise and it remains for those who undertake such work to excel in its performance and to suggest ways and means for its betterment. Specifications and drawings, known as type plans, are issued covering all the apparatus, appliances, and materials entering into the equipment. Each bureau of the navy department compiles the requirements for the work under its cognizance and in this manner provides for its inspection both at the works



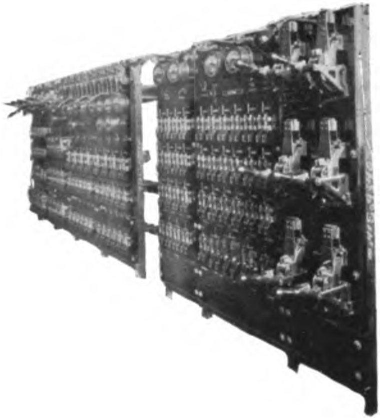
[HORNOR]

SMALL GEARED TURBINE GENERATING SET FOR MERCHANT SERVICE WITH CASING REMOVED



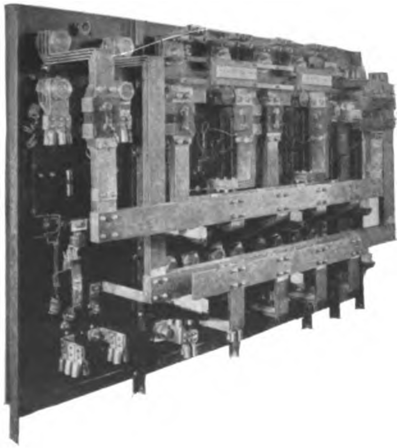
[HORNOR]

MERCHANT TYPE MARINE GENERATING SET—AUTOMATIC GRAVITY LUBRICATION



[HORNOR]

FRONT VIEW OF NAVY STANDARD SWITCHBOARD



[HORNOR]

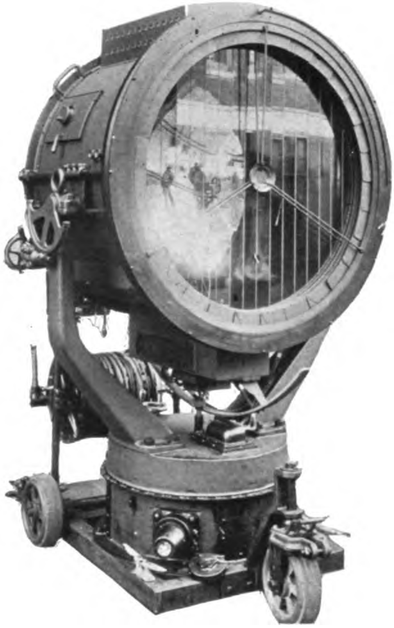
REAR VIEW OF NAVY STANDARD SWITCHBOARD SHOWING CONSTRUCTION DETAILS

of the manufacturer and at the plant of the contractor. The bureau of steam engineering, the bureau of Construction and Repair, the Bureau of Ordnance and the Bureau of Navigation are the bureaus most nearly touching the electrical installation; the Bureau of Steam Engineering and the Bureau of Construction and Repair performing the most essential parts of the work. The generation of electricity, its control, distribution, installation and maintenance fall under the administration of the Bureau of Steam Engineering, and the provision of the motors and their control for the various deck and other machinery come under the direction of the Bureau of Construction and Repair. The turret motors and questions connected with gun fire are under the jurisdiction of the Bureau of Ordnance and special equipments connected with the operation of the vessel when under way, such as gyroscopic compass are taken care of by the Bureau of Navigation. All type plans issued by the Bureaus whether of apparatus, etc., or for the construction work are simply guides or schedules from which elaborated drawings must be made embodying correct designs and full details. These drawings must be forwarded to the bureau, or bureaus, involved and receive formal approval before work may proceed. In the case of apparatus newly designed drawings must be submitted to the bureau concerned for its approval as a type after which approval must be again obtained for its specific application. After an installation or apparatus is completely finished, inspected, and received, a complete set of drawings of the final details must be prepared and turned over to the Government. Due to this procedure the materials entering into the construction of naval apparatus are in every way of a higher grade than those employed in merchant service.

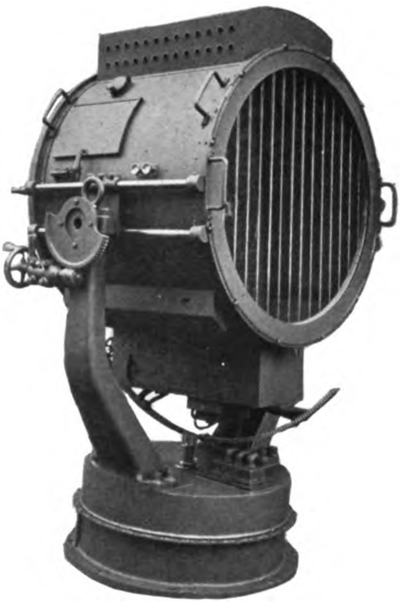
The use of iron conduit and open wiring supported on insulators has now given place to armored conductors. There are conditions which require different types of wire so that the specifications permit of three general types, namely, plain conductors, armored, and lead-covered armored. The practise at the present time is to use lead-covered armored cables for all permanent leads throughout all spaces in the vessel. The best quality of rubber, linen, jute, lead, copper and steel are required. Cables are clipped rigidly to the structural parts of the vessel by strap hangers and when a group of leads occurs or at the structure is such as not to permit a compliance with the above, a five-pound steel plate is first fitted and the armored wires attached to this

plate. These cables are sufficiently flexible to allow of close fitting or "nesting" and thereby much space is conserved and a better appearing installation results. In addition to these advantages is the reduction of upkeep over conduit due to a decrease in the deterioration of the insulation by its protection from condensed moisture. Stuffing tubes as in merchant practise but of special design are required when passing through decks or watertight bulkheads. Through non-water-tight bulkheads they are led through holes with the edges rounded off. Mechanical protection is also provided near the walking spaces at decks and at other particular locations where the cables would be unduly subjected to abuse, or would themselves subject the contents of the compartment to danger. In the vicinity of the magnetic compasses the steel braid is removed. For the convenience of testing and designation, the cables are all carefully and accurately tagged in accordance with approved plans. No splices are permitted and mechanical joints are all made in specially designed watertight brass boxes. All feeders for every purpose must be continuous throughout their length except in especially long leads of the larger size cables when proper mechanical connections are allowed in order to facilitate installation and avert damage to the cables by the severity of the necessary handling.

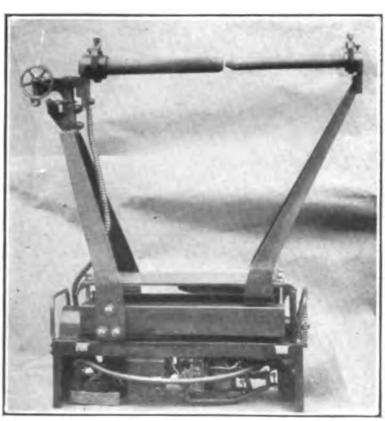
The distribution of energy is on the two-wire system. The lighting, and small power feeders are run from the main switchboard to centers of distribution and mains led from thence to the terminal apparatus. Mains may also be taken directly from the feeders to meet the conditions of structural obstructions. Distribution boxes of brass are provided of varying types some containing knife switches and fuses, others with fuses only, others with fuses and snap switches. These also vary in mechanical construction some being water-tight and others non-water-tight to suit the location. Twin conductors up to 60,000 cir. mils are permitted, and branch leads for lighting must not be less than 4000 cir. mils. The permissible drop on the lighting system from the main switchboard to the farthest outlet is $2\frac{1}{2}$ per cent and for power 5 per cent. The carrying capacity of all conductors is based on one thousand circular mils per ampere for continuous loads and five hundred circular mils for intermittent loads. The permissible drop on the signaling systems is $2\frac{1}{2}$ per cent when lamp instruments are used and not over 5 per cent on circuits containing bells, buzzers, push-buttons, contact-makers, etc.



[HORNOR]
THIRTY-SIX INCH PORTABLE SEARCHLIGHT NAVY STANDARD



[HORNOR]
THIRTY INCH NAVY TYPE DISTANT MECHANICAL CONTROL SEARCHLIGHT



[HORNOR]
MOTOR-FEED LAMP MECHANISM FOR NAVY STANDARD SEARCHLIGHT

[HORNOR]
TWENTY-FOUR INCH NAVY TYPE SEARCHLIGHT VENETIAN BLIND SHUTTER

Generators for naval service are generally direct-driven by steam turbines, mounted on a common bed-plate. The turbines are of the horizontal type and designed for both condensing and non-condensing operation. They must be capable of operating the generator indefinitely at one-third overload. They are required to operate automatically with load varying from zero to $1\frac{1}{3}$ load. They must function with the most economical water rate possible when supplied with dry saturated steam at 200 pounds pressure and 25 inches vacuum. Forced lubrication is specified for all sizes, and the largest sets have their bearings water-cooled. Gages for observing the vacuum in the exhaust, main steam pressure, oil pressures, etc., and indicators for inspecting the flow of oil and cooling water to bearings, tachometers thermometers, pilot lights, etc., etc., are all provided. The generators are direct-current compound-wound, and in the larger sizes supplied with commutating poles. The frame is circular in form and in the largest sizes split horizontally. These are the essential differences from regular practise with the exception that exhaustive tests are made in order to secure compliance with the specifications. At the present time the navy requires its generators on battleships wound for 240 volts but for smaller craft retain a potential of 125 volts. In order to obtain increase in economy, reduction gears with high-speed turbines are now being installed and have received formal sanction. Sets of this design have reached the first stage; namely, shop tests. The change in voltage to 240 on the larger vessels has brought about the necessity for a neutral bus to supply the lighting and searchlight systems. This may be accomplished either by a three-wire generator wound for operation with a compensator; or an auxiliary independent rotary balancer set. Both methods have now been introduced but service operation has not yet been fulfilled.

Until recently the switchboard panels were made of carefully selected slate. Now the requirements call for a special composition material having a high insulation resistance and unaffected by steam, or moisture, or shrinkage, when subjected to differences in temperature or hydroscopic changes and capable of a certain deflection without breaking. All the instruments mounted on the switchboard are specified in detail and only approved instruments and fittings are permitted. Enclosed fuses are approved if they conform to the general requirements of the national electric code. Renewable enclosed fuses are

allowed under the requirement of a special specification for fuses. Detail requirements are issued for all bus-bar construction, fittings, bolts, etc., all of which must be suitable to withstand the severe atmospheric conditions of shipboard service.

For the larger vessels the government furnish 36-inch distance control searchlights and 12-inch signal searchlights. The larger projectors are arranged so that some of them may be placed on trucks and transported about the decks. On the smaller vessels, 30-inch and 24-inch searchlights, with mechanical distant control, are installed. All lamp mechanisms are of the motor type and both venetian blind and iris shutters are provided. The plain glass front frame is supported on springs so as to take up the shock of gun fire. A finder similar to that used on a camera is fitted so that it will show on a ground glass screen the arc, and by means of cross hairs enable the arc to be placed in the proper focal position and the carbons correctly adjusted.

Lighting fixtures and appliances are all made of brass composition and are heavier in every sense than the merchant marine type. However, the navy has now discarded the spring type of socket and adopted that used in commercial practise, with the difference that a special insulation material is provided for the base instead of porcelain. The fixtures installed in quarters and general living spaces are designed with a special shade holder, similar to that used in railway cars, whereby the shade is held in place by a spring and not dependent upon screws. Guards are required on steam-tight fixtures in open spaces where subject to mechanical injuries. Prismatic glass globes are fitted in all steam-tight fixtures and special shades are employed to direct and diffuse the light. Tungsten incandescent lamps are in general use but locations greatly affected by vibrations are lighted with carbon filament lamps. The high wattage tungsten lamp has now superseded both the carbon and mercury arc lamps for the illumination of large spaces.

Motors are designed under a special specification which enters into minute details so that a best service under sea conditions may be obtained. They are wound for either 120 volts on smaller vessels or 230 volts on the larger. In sizes of five h.p. or over they are multipolar, preference being given to comutating pole type. Various types of motors differing in mechanical construction as well as electrical characteristics depending upon the location and the service are required. For spaces and condi-

[HORNOR]
NAVY STANDARD DECK FIXTURE

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NAVY STANDARD GANGWAY FIXTURE

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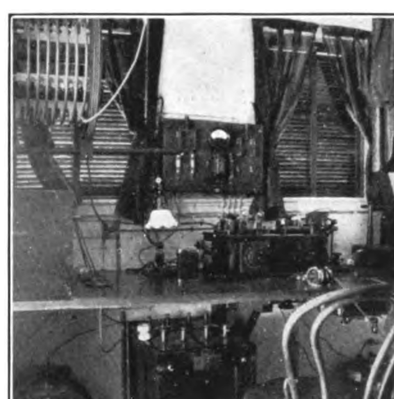
NAVY STANDARD FUSED FEEDER BOX



[HORNOR]
MERCHANT TYPE WIRELESS STATION

Two-kw., 240-cycle, installed on freight vessel.

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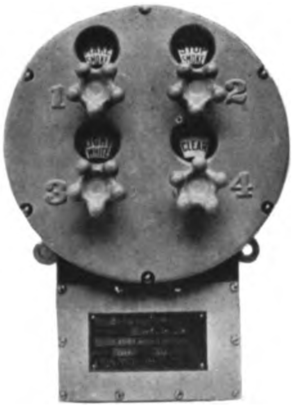
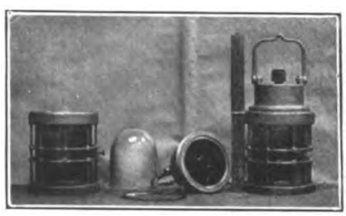
MAJOLICA FIXTURES



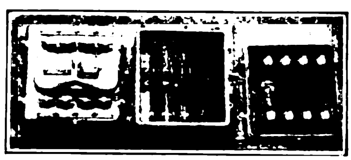
[HORNOR]
SMOKE TELEGRAPH TRANSMITTER

[HORNOR]
SMOKE TELEGRAPH INDICATOR

[HORNOR]
NAVY STANDARD BATTLE LANTERN SUPPORTED ON SPRINGS FOR TURRENT INSTALLATION

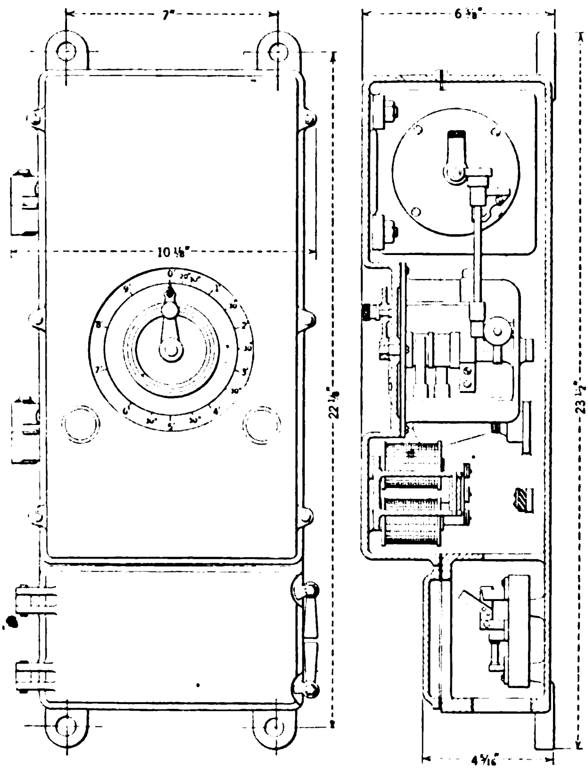


[HORNOR]
NAVY STANDARD BATTLE LANTERN



[HORNOR]
NAVY STANDARD FUSED SNAP SWITCH—WATERTIGHT DISTRIBUTION BOX

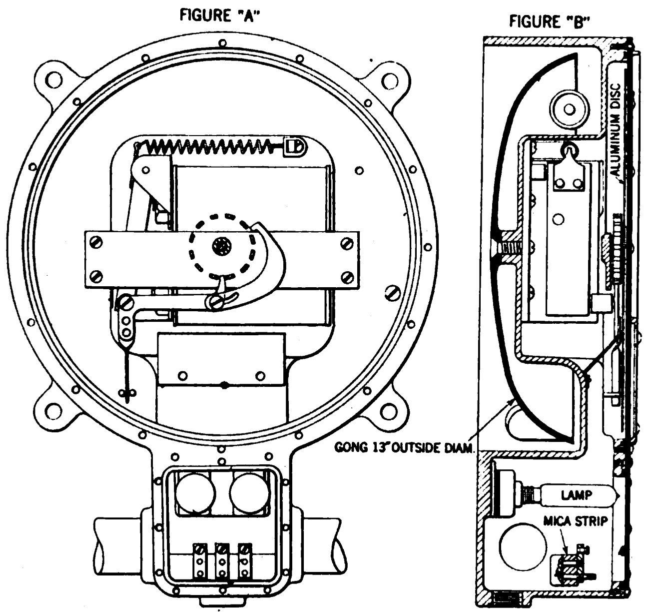
tions where water or moisture cannot damage the apparatus open or semi-enclosed motors are permitted; on the other hand where exposed to the weather or moisture they are totally enclosed and of water-tight design. Enclosed ventilated motors are approved for specific conditions. Non-corrosive parts and interchangeability are of great importance. Much attention is given to the testing of such apparatus and specific instructions are given



TRANSMITTER FOR BOILER FIRE TIMING DEVICE—MOTOR REVERSING TYPE

covering the adjustment, heating, balance, dielectric strength, efficiency, weight, etc. The tests are usually made at the works of the manufacturer and no shipments can be made until the apparatus meets the full requirements of the specification. Three types of control are now required in order to cover the various power equipments; namely, panel type controllers, drum-type controllers, contactor type controllers. These are

mounted in water-tight enclosing cases where conditions demand in the same manner as for motors. Contactor panels usually being of large size are located below decks where they can be mounted like switchboards. They are operated automatically by a master controller which would be of the water-tight pattern if located on the weather deck. To insure against unauthorized handling these contactor panels are usually protected by an expanded metal enclosure. Spare parts must be supplied with all motor and control equipments. These parts are based upon



FRONT VIEW WITH COVER AND DIAL REMOVED SECTION THROUGH CENTER LINE

INDICATOR ELECTRIC TIMING DEVICE FOR BOILER FIRING

the number and type of apparatus used; they are subjected to a like test as the motor, and are carefully packed in special boxes and marked for identification.

The signaling systems are installed under the same rules as regards cables, methods of distribution, methods of securing the cables, etc., as already described. Energy for these systems is taken from the lighting bus-bars and transformed by means of small motor generators, or dynamotors, to a low potential (20 volts d-c.). A special cable is designed for the general systems and one composed of like materials but with the wires twisted

[HORNOR]
RUDDER INDICATOR

[HORNOR]
ELECTRIC DOCKING TELEGRAPH

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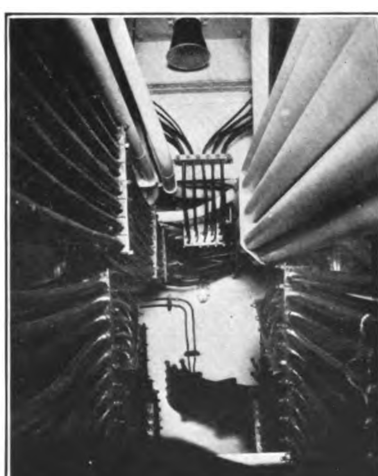
ENGINE ORDER TELEGRAPH TRANSMITTER

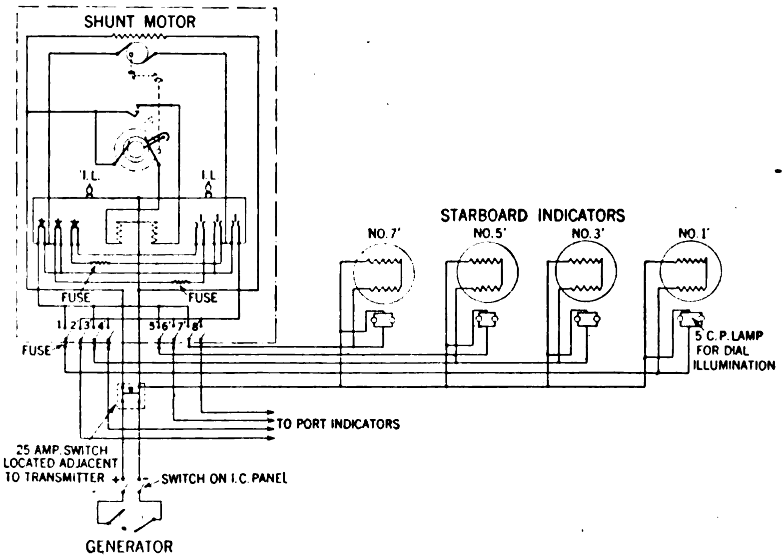
[HORNOR]
SHAFT SPEED INDICATOR



[HORNOR]
CABLES AND VOICE TUBES IN WIRING PASSAGE ON BATTLESHIP

[HORNOR]
NAVY STANDARD NIGHT SIGNAL KEYBOARD

and paired for the telephone system. As the instruments for this application are usually more delicate than the other apparatus it is more essential that care be exercised in their manufacture, and the points brought out previously must be even more precisely looked after. The d-c. motor-operated instruments have superseded the lamp instruments almost entirely, and they seem to be providing very satisfactory service. Communication systems play an important part in the navigating of the vessel, in the transmission of general orders, and in the signals for gun



Transmitter Wiring Diagram for Boiler Firing Device—Motor Reversing Type

firing. These systems are very expensive and command as much attention and special designing as the power system.

Installations on Various Types of Vessels

The general requirements of both merchant and naval practise having been described, a brief outline of the electrical equipment on a few typical vessels will be given. It is to be understood that such installations are so flexible that many things are done for no better reason than that of individual preference; but these descriptions will endeavor to show the present extent of the application and the trend of development.

LAUNCHES AND YACHTS

Certain manufacturers design and build complete outfits including generator, switchboards, and storage batteries, especially for this service. For the amateur yachtsman who delights in the experience of experimentation these outfits may do well. The generator is usually operated by a friction pulley on the flywheel of the propelling engine and the storage battery is used for steadying the voltage and supplying energy when the main machine is not in operation. A better equipment is found in the larger steam yachts and for steam launches for large vessels. Such craft are fitted with a one-kw. direct-connected steam turbine generating set preferably of 110 volts. Standard lamps and standard searchlights may then be installed. No attempt is made for any expensive distributing systems but a special fused circuit is provided for the signal lights. The fixtures are usually selected by the owner and the style and type corresponds to the decorations. All the fixtures of a house installation are followed and the applications merely depend upon the luxury desired.

TUGBOATS, FIREBOATS, ETC.

Sea-going tugs usually carry two generating sets of 10 kw., 110 volts, one 18-inch searchlight, the usual signal lanterns, including towing lights and approximately 120 incandescent lights. Government tugs in addition to this are supplied with a submarine signal receiver set, a night signal set, a call-bell system, and wireless telegraph outfit.

Mine-planters and lighthouse tenders for the government have a generating plant arranged to carry the day and night load instead of the customary duplicate generating set. One turbo-generating set has a capacity of 7 kw. and the other 20 kw. Besides this they are supplied with a submarine receiving set and frequently with a wireless outfit. The installation and installation material must conform to naval practise. Approximately 120 to 150 lights are installed.

DREDGES

The ordinary merchant type dredge has an installation of approximately 150 lights, carries one or two searchlights depending upon the length of the vessel and uses the high wattage tungsten lamp in lieu of the arc lamp. The generating plant consists of a total of 20 kw. usually comprising two 10-kw. marine reciprocating engine-driven generating sets. Special searchlights simi-

lar to those used in the Suez Canal, are available for this type of vessel. A diverging lens is placed on the searchlight barrel and the rays are thrown to each bank of the stream and leave a dark space ahead. This permits of up and down traffic without interfering with the regular signal lights. There is a growing tendency toward the use of electric power for the main purposes of dredging, and experimental plants are now in service in the western part of this country. There would seem to be no important reason why such an application should not be entirely satisfactory and economical.

Ferryboats

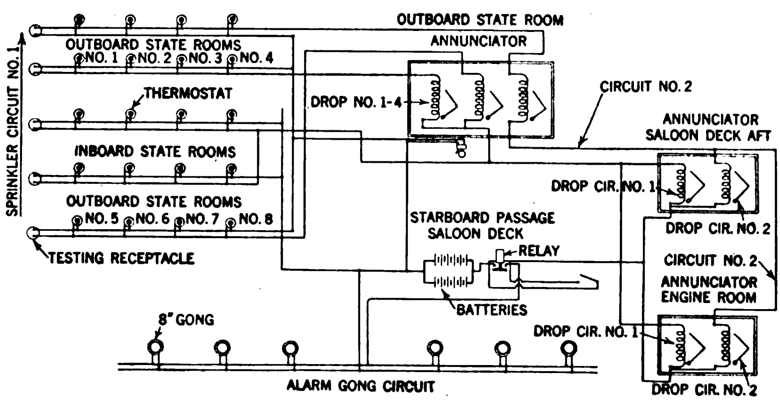
The general practise today in lighting ferryboats is to outline the cabins with 25- or 40-watt tungsten lamps. These circuits are arranged so that in cases of emergency every other light may be in operation and total darkness avoided. Two generating sets, one of small capacity for the daylight load and one of large capacity for the night load, are furnished and the circuits as above described are designed so that it will not be possible to overload the smaller generating set. The average ferryboat is lighted by approximately 225 incandescent lamps. An interesting mechanical signal is connected to the disengaging gear of the steering engine and automatically warns the engineer at which end of the boat the steering gear is working. The signal lights are also so wired that when the pilot unlocks his steering wheel the correct lights for that direction go on and the other set of lights go off.

Excursion Steamers

For river and lake traffic two types of vessels are designed—those that make night trips and those that make short day-light pleasure trips. The day boats are usually equipped with a duplicate dynamo installation. They are lighted by approximately 300 to 400 lights and carry one 18-inch searchlight. As these vessels are light in construction, of shallow draft and do not encounter severe storms it is possible to adapt modern methods of illumination and so it will be found that indirect and semi-direct fixtures are installed with ample reason because of the higher deck spaces and the artistic effects of the decorations.

The larger Sound and Lake steamers are floating palaces and require the best of the decorator's art to satisfy the owner's desires. Much space in the super-structure is devoted to general rooms and these, often occupying three decks, are sumptuously

furnished. All the artifices of the lighting expert are requisitioned; and concealed incandescent lamps back of the light wells, lights in glass columns, lights for the paintings, garlands of small lights, newel post lights, semi-direct and indirect lighting units—all these and many more go to make up the appearance of luxury which is required. Such vessels are equipped with plants ranging from 100 to 200 kw. One of the interesting installations which differ from other vessels is the fire alarm system which becomes of great importance due to the liability to fire and the large number of lives involved. As an illustration of the care observed in such matters the installation of the fire alarm system on the Sound steamer " Commonwealth " may be considered typical. The system was the open circuit type.



WIRING DIAGRAM—THERMOSTAT SYSTEM

Mercurical thermostats of navy pattern were installed. A testing receptacle is located at the end of every line and tests are made every day after the passengers have left the vessel. The collision and general alarm gongs located throughout the vessel are also operated by this system, as well as by the regular switch installed in the pilot house. The system is energized by both the regular interior communication dynamotor and also by batteries which are thrown in automatically if for any reason the dynamotor is not running. The bells throughout were of the short circuit type in order to eliminate the possibility of an open circuit in the bell. The annunciator in the engine room was located at the valves for the sprinkler system so that response by water could be immediately given. The saloon deck annunciator was a duplicate of the engine room instrument and the eight

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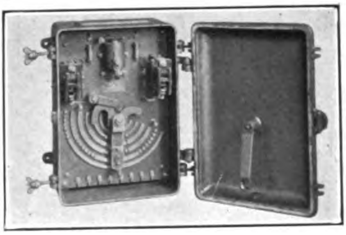
NAVY STANDARD CHAIN AMMUNITION HOIST MOTOR



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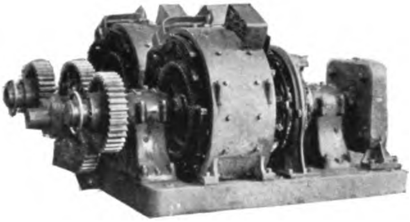
U. S. NAVY WATERTIGHT CONTROL PANEL FOR CHAIN AMMUNITION HOIST MOTOR



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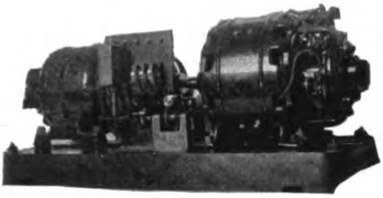
U. S. S. NEVADA STEERING GEAR MOTORS 125-VOLT CONTACTOR SYSTEM



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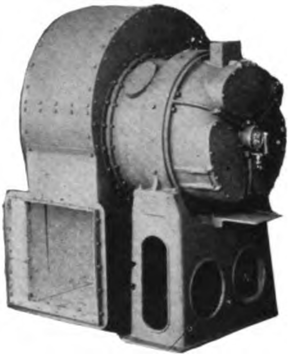
TIME CONTROLLED MOTOR-GENERATOR SET FOR SIGNAL HOWLERS



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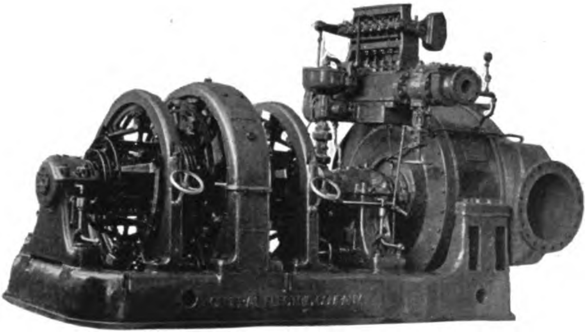
NAVY STANDARD VENTILATING FANS



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TURBO-GENERATOR UNIT—300 KW. 1500 REV. PER. MIN. 125-VOLT

local annunciators had the circuits sub-divided in order to facilitate testing and upkeep.

Freight Vessels, Colliers and Oil Tankers

Freight vessels of 5000 tons dead weight carrying capacity are usually equipped with 10-kw. marine reciprocating-engine generating sets in duplicate. Approximately 150 fixtures, a few portable hand lamps, cargo reflectors and one 18-inch searchlight which is mounted on the top of the pilot-house and controlled from the inside, are furnished. With the exception in a few cases of a small inter-communicating telephone system, the signaling systems installed are only those required by law.

The equipment of oil tank vessels differs only slightly from that of regular freighters and colliers. The generating sets are usually a little larger, about 15 kw., and a few more lights are required, depending largely on the arrangements of the vessel. The location of the main propelling machinery, whether it is in the extreme after part of the vessel or amid-ships, naturally affects the extent of the electric plant. The owners of such vessels often take great precautions and insist on special designs of fixtures and fittings. In some cases great care is exercised in the permanent fixtures located in the pump rooms, these embodying a special sealed globe so as to prevent the entrance of oil fumes, and in other cases the owner prefers the use of navy standard fixtures in this particular compartment. Some owners require these special fixtures to be furnished throughout the vessel except in living spaces, and other owners use the regular commercial fixture except in the pump room. Up to the present time electric power has not been extensively employed for the operation of the important auxiliaries but it is not believed that direct-current motors would be as safe or as ready of service as alternating current.

Coastwise Passenger and Freight Vessels

Such vessels are more elaborate and so the electrical equiment becomes larger and assumes greater importance. These ships carry electricians so that the questions of reliability and readiness of service do not enter to such an extent as on smaller and less important vessels. The service that the owners wish to give and the demands of the public who travel in these coastwise vessels determine many of the applications of electricity. So it will be found that some of our coastwise vessels especially

on the Pacific coast have a complete electric air heating system because the evenings on the West Coast are sometimes chilly and it would not pay the owners to install a steam system for so infrequent a service. On the Atlantic coast the winters are severe enough to require steam heating. As an illustration of the type of electrical installation on coastwise vessels, the equipment of the S. S. *Great Northern* and the S. S. *Northern Pacific*—vessels recently completed for the Great Northern Pacific Steamship Company, will be described.

The generating plant consists of four 35-kw., 110-volt, direct-current, commutating-pole, compound wound generators direct-connected to 3200-rev. per min. water-cooled bearing turbines, supplied normally with steam at 200 pounds and a vacuum of 28 inches, and designed to carry full load at 175 pounds steam pressure and 10 pounds back pressure. Each generating set is connected to the main distribution board through an automatic circuit.

From the main switchboard are led 24 feeder circuits supplying lighting, searchlights, hull ventilation, supply and exhaust fans, cargo elevators, galley and pantry motors, as well as a shore feeder of sufficient capacity to light the entire vessel from a shore plant, or light the dock from the ship's generator. The wiring is on the two-wire system, and the material used represents the very latest marine construction. The highest grade rubber-covered wire is used, over which is supplied a lead sheathing, this being protected by a basket weave galvanized steel wire armor. This wire is secured directly to the structure of the vessel eliminating customary conduits and moulding and the collection of moisture in them—the cause of numerous troubles, experienced with conduit installations. Water-tight junction and feeder boxes and fixtures are used throughout except in living quarters, and the wire entering these applicances is made water-tight by hemp packing in suitable stuffing tubes. Mazda lamps are used throughout the vessel, of which there are 1700. The lighting circuits are divided into four classes—general illumination used as required, stateroom lighting always at the disposal of the passengers, police lights which are never extinguished, and the individual cargo lighting throughout the cargo spaces controlled by separate circuits so that the lights may be extinguished when the cargo spaces are filled in conformity to the insurance requirements. Every passenger compartment is supplied by duplicate feeders so that in the event of a failure

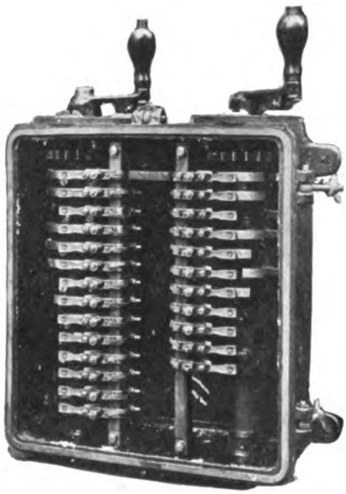
of one feeder no compartment is in darkness. The lighting fixtures are unusual in several features. Majolica fixtures decorated in gold are used in the staterooms and stateroom passageways. This is the first use of such fixtures in this country. Each stateroom is provided with a receptacle of the same construction for reading lamps, fans, curling irons, or warming pans. Steam and water-tight fixtures are used in exposed locations, machinery and cargo spaces. The reflected lighting for the oil paitings in the saloon, lobby, writing room, and "*A*" deck entrance, as well as the massive semi-indirect lighting fixtures used exclusively in the dining room, are departures in marine work. All metal parts in the stateroom are of monel metal to eliminate plating and prevent discoloration. Cameo and cut glass bowls of various designs for lighting fixtures have been used quite extensively throughout the vessel.

The ventilation and heating of the vessel is most complete. Fourteen ventilation and heating units supply all staterooms and public spaces. These consist of conicle flow fans used for the first time in marine work and which on test develop an efficiency of 56 per cent. These fans are direct-connected to enclosed adjustable-speed motors and discharge the air through coil heaters. All these units are supplied with a by-pass for use when not required. These units range in size from 1500 to 3000 cubic feet of air per minute at 11 pounds per square foot pressure, and are designed to supply the full quantity of air when discharged through the heater. Six fans of the same type without heaters are used to exhaust the air from lavatories, toilets, galley, pantry and smoking rooms, and, when run at maximum speed, will change the air in these compartments every minute. Electric motors are used quite extensively in the galley and pantry where the following apparatus is located: One one-barrel dough mixing machine operated by a two-h.p. motor, one 40-pound vegetable paring machine operated by a ½-h.p. motor, two one-tank dishwashing machines operated each by a ½-h.p. motor, one meat and food chopping machine operated by a one-h.p. motor and capable of chopping 144 pounds of food per hour, one 2800-watt, three-heat hotel griddle used for toasting bread, frying eggs, bacon and chops. The large cold storage compartment which extends the width of the vessel, as well as each of the cargo holds, is provided with a three-ton hoister operated at a speed of 100 feet per minute and driven by a 40-h.p. motor equipped with automatic starting and limit switches.

The call-bell push buttons in all the staterooms have been utilized as a part of the fire alarm system by the installation of a thermostat button which expands when subjected to a temperature of 160 deg. fahr. This will announce on the call-bell annunciator an excess of temperature in the particular location even if the room is not occupied. The main fire alarm system, consists of a small pipe of minute internal diameter which is carried throughout the living spaces of the ship. An indicator board representing small plans of the different decks is mounted in the pilot-house and small battery lamps give the location of the fire upon the sounding of the alarm. This system is based on the expansion of air due to increase in temperature. The latest improved loud speaking telephones are used for communication between locations exposed to weather conditions and machinery noises. A commercial standard type of telephone is used for communication between other locations. A motor-driven type of electric whistle operator is installed with switches located in a number of places both for blowing the whistle at will and also for blowing the whistle automatically during foggy weather. The vessel is equipped with the usual mechanical engine and docking and steering telegraphs of the latest and largest pattern.

A powerful-18-inch searchlight is mounted on each end of the forward bridge in such a position that they can sweep the entire length of the vessel.

This vessel carries two wireless outfits both of the navy type, one of two-kw. capacity and the other of ½-kw. The latter was for emergency purposes and could be operated from the battery. Every precaution was taken in mounting the apparatus, which was extremely compact, so that if the ship were sinking the wireless telegraph station would be in service until the water reached the radio room. The motor generator for the largest set was supplied energy from the ship's 110-volt system but could also be energized from battery. The batteries were automatically charged and the machinery in general so controlled. All the apparatus was protected from induced high potentials by means of condensers and protective resistors. The transmitter was the quench-gap (noiseless) type, 500 cycles. A blower was used to cool the surface of the quench-gap plates. The transformer stepped the 220 volts of the generator to approximately 12,000 volts. The oscillation transformer was constructed of copper ribbons edgewise wound, spiral mounted on hard rubber



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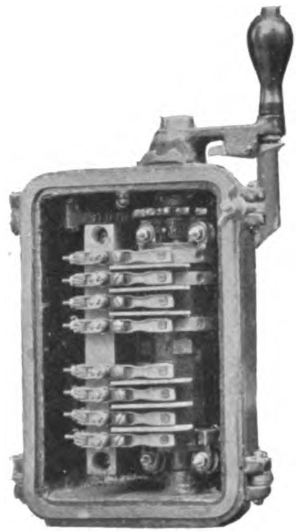
DOUBLE WATERTIGHT MASTER CONTROLLER FOR BOAT CRANES ON U. S. S. ARIZONA



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WATERTIGHT MASTER CONTROLLER FOR CAPSTAN ON U. S. S. ARIZONA

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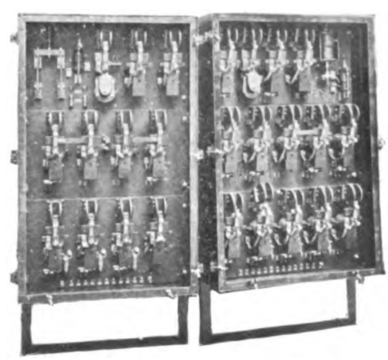
FORTY-FIVE H. P. CAPSTAN CONTACTOR PANEL ON U. S. S. ARIZONA



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TWO 50 H. P. BOAT CRANE CONTACTOR PANELS ON U. S. S. ARIZONA

One for hoisting on the right, rotating on the left.

disks. The aerial inductance for lengthening the wave of the open circuit is likewise constructed. A condenser of four plates in series serves to shorten the wave. A protective reactance is connected across the sending key. The receiver detector is of the carborundum crystal type, and sensitive head telephone sets are used. The aerial is of the two-wire "*T*" type with 14 feet spread between wires. The main set has given remarkable service. Communication at night was uninterrupted from the time the vessels left Philadelphia until it arrived at Santiago. The *Great Northern* on a trip from San Francisco to Honolulu retained communication by night from the time of her departure from San Francisco until her return. The power of the large set may be varied from 100 watts to 3000 watts and while the set was being tested at her builder's yards in Philadelphia, Cleveland, Ohio, was called at 6:30 p.m., using 600 watts, and answered immediately. Boston was communicated with about a half hour later using 250 watts.

Submarine Boats

The energy for the lighting and power system is supplied from the main storage batteries. The lighting supply contains a dimmer by means of which the 110 volts may be maintained reasonably constant. Approximately 40 to 60 steam-tight guarded fixtures are installed. The auxiliary motors, such as for ventilation, pumps, air-compressors etc., are of standard design wound for 120 volts. The main propelling motors are wound for 120 to 240 volts. These operate as generators when the vessel is on the surface for charging the storage batteries. There are three separate switchboards, one for the main battery, another for the lighting and power systems, and a third for the interior signaling systems. These latter consist of telephones, call-bells, engine telegraphs, torpedo tube indicators, marker buoy, submarine signals, gyro-compass, and wireless telegraph. Remote control systems are much employed especially for such systems as the diving apparatus, steering gear, and the elevating gear for the periscope.

Torpedo-Boat Destroyers

The growth of the generator plant for torpedo-boat destroyers has been very marked in the last few years and two 25-kw. 125-volt turbo-driven sets are now installed. Approximately 200 incandescent lights, two 30-inch searchlights, a night

signal set, electric fans, hull ventilation, and a system of interior communication comprise the equipment. This latter system consists of call-bells, general alarm gongs, smoke indicators, shaft revolution indicators, torpedo firing, and wireless telegraph. These instruments are exactly similar to those used on battleships, the size of torpedo-boat destroyers now being such that no modifications are necessary in order to adapt the standard instruments.

Fleet Auxiliary Vessels

The navy has many vessels such as transports, supply ships, colliers, submarine tenders, torpedo-destroyer tenders, etc., all of which serve some necessary purpose in attending the fleet. Though these vessels naturally differ in their arrangement, size, etc., still they all more or less carry about the same electrical equipment. This equipment usually consists of a turbo-generating plant of approximately 300 kw., 125 volts, necessary switchboard, four 30-inch mechanically controlled searchlights, about 700 to 800 incandescent lights, two night signaling sets, electric fans, hull ventilation, and a system of interior comunication. The signaling system comprises call-bells, fire alarms, general alarm gongs, boat hour gongs, telephones, shaft revolution indicators, helm angle indicators, electric whistle operator, fuel oil indicator, submarine signals, and wireless telegraphs.

It is interesting to note in this connection that the fleet collier *Jupiter* is equipped with electric motors for the purpose of propulsion and that this vessel is the first sea-going vessel so propelled. The *Jupiter's* installation has been fully described both when designed and after she performed her trials. She has now been in regular service about two years and has shown very successful performance. This installation was an experimental one and was purposely made for comparison with reciprocating-engine drive and geared-turbine drive, the same type of vessel being maintained in each case. The *Jupiter* has shown herself very much superior to the reciprocating engine-driven ship and comparisons cannot be made with the geared turbine-driven ship as data from this vessel has not yet been made available.

Battleships

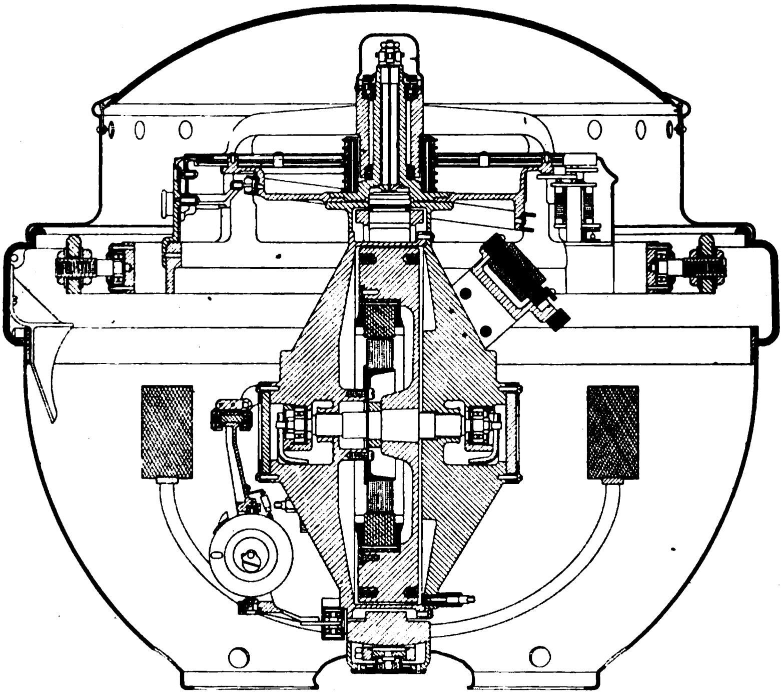
The electric plant consists of four 300-kw. turbine-driven, direct-connected generating sets of 240 volts, direct current. Two sets are located forward and two aft. These sets are either three-wire machines or two-wire; in the latter case rotary balancer

sets are required so as to provide 120 volts for the lighting and searchlight systems. There are two main switchboards installed fore and aft in special compartments. These switchboards control the generators and distribute the energy for power and lighting. A common negative bus and a separate positive lighting and power bus enable a separation between these two systems. The two distribution boards are interconnected so that energy may be supplied to either board from the other. The generators in each room are operated is parallel but the two rooms are so arranged that multiple operation is not possible. Auxiliary switchboards are furnished for the further distribution of energy and form the centers of distribution for the feeding system. Eight 36-inch searchlights and two portable 12-inch single projectors are furnished.

The lighting system consists of 3000 regular standard fixtures, and an auxiliary lighting system is provided for the more important working spaces of the vessel; this system is supplied by batteries. Each turret has an independent auxiliary battery lighting system. There are installed 135 electric bracket fans, an electric heating system, a complete interior communication system, and a complete system of power-driven deck auxiliaries.

The power system comprises electric-driven hull-ventilation fans and heating coils, turret turning, turret ammunition handling, turret gun ramming, turret gun elevating, boat cranes, deck winches, capstan, five-inch ammunition hoist, ammunition conveyors, sanitary, fresh water, main drainage and secondary drainage pumps, air-compressors, anchor windlass, steering gear, independent laundry equipment, independent workshop machinery, main turbine turning equipment, independent commissary appliances, such as dough mixers, ice cream freezers, meat choppers, potato peelers, dish washers, etc., and the energy supplied to bake ovens. Of these equipments the largest is the steering gear and two systems—the contactor control and the motor-generator control—are now in the trial stage. This system requires a motor rated at 350 h.p. and capable of working under a hundred per cent overload for a few minutes. The steering gear application has recently been described and as no trials of the apparatus now installed have been held nothing can be added to this subject at this time. Next to the steering gear equipment in size, is the anchor windlass, requiring two motors of 175 rated h.p. and the same overload capacity as the steering gear motor.

The interior communication system comprises the following: call-bells, telephones, fire alarm, general alarm gongs, boat hour gongs, shaft revolution indicator, steering telegraph, steering emergency signal, gyroscopic compass, engine revolution telegraph, fire room telegraph, engine order telegraph, loud-speaking telephones, rudder indicator, gun firing systems, warning systems for closing water-tight doors, air-lock indicators for indicating when air-lock doors are open, water-tight door

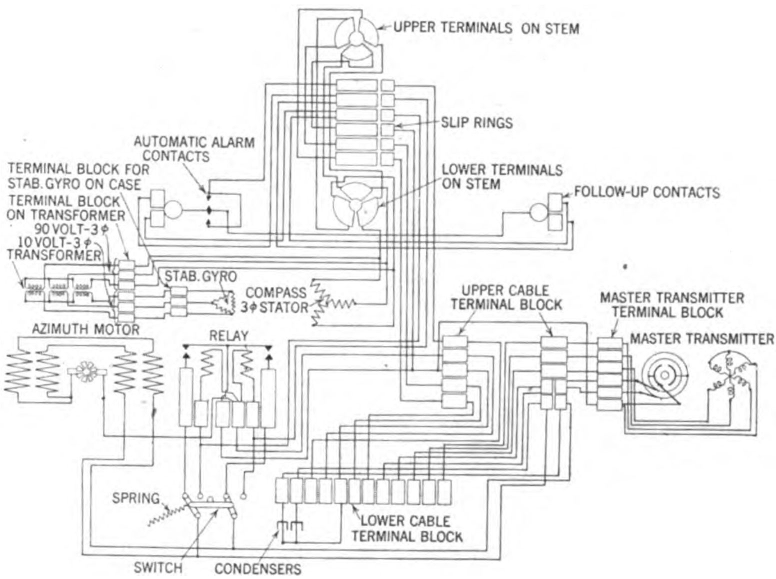


MASTER GYROSCOPIC COMPASS

signals, submarine signal, electric whistle operator, drainage tank indicator, and wireless telegraph. One of the most interesting developments among these many systems is that of the gyroscopic compass. This apparatus has been recently described and its application has been greatly extended in various ways.

It is to be noted that the experiment with electric propulsion on the *Jupiter* has been so satisfactory that our government has authorized its installation on the U. S. S. *California*, one of the latest battleships now building at the New York Navy

Yard. The design of the motors will differ slightly from those of the *Jupiter* but the general applications will be the same. A total of 37,000 h.p. will be provided, and each of the four shafts will be operated by an induction motor receiving energy from two steam turbine-driven alternators wound for approximately 2500 volts three-phase. The advantages to be gained in this electric coupling, instead of the mechanical reduction gear, are very obvious in the case of a battleship, as it is necessary at certain times to drive the vessel at high speed but it



INTERNAL WIRING OF MASTER COMPASS, WITH MASTER TRANSMITTER

is just as necessary to drive it under normal conditions at low speed; for this large variation in horse power the electric equipment is more flexible and more economical, permitting of like water consumption at low, intermediate, and high speeds. The motors are provided with two windings using the slow-speed winding at ship's speeds lower than 15 knots and the high-speed winding at higher speeds. One generator will supply all four motors for intermediate speeds and each generator will supply two motors for full power.

Conclusion

Merchant marine applications have not shown a like increase to naval applications because of the lack of a merchant overseas trade. Trans-Atlantic and Trans-Pacific vessels of the foreign type have not been constructed in this country since 1902, at which time a vessel of 12,000 tons and 620 feet long was considered a large vessel; these cannot be compared with the present day vessels of over 900 feet in length and over 30,000 tons displacement. The naval applications have advanced because our naval strength depends upon the efficiency of the vessel and her equipment. It is to be expected that when our country develops a merchant marine that many of the advances made in naval practise will be found advantageous to merchant vessels.

It is interesting to note that the cost of the electric propelling apparatus for the U. S. Battleship *California*, inclusive of electric engine room auxiliaries, was approximately eleven dollars and sixty-five cents per shaft horse power—less than half the cost of the electric plant.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 17, 1915.

OVERHEAD ELECTROLYSIS AND PORCELAIN STRAIN INSULATORS

BY S. L. FOSTER

ABSTRACT OF PAPER

There is a slight leakage of current from trolley wires to earth through insulated supports on all electrical overhead construction, which if not checked permits a flow of current which gives rise to electrical separation of water into oxygen and hydrogen. The oxygen liberated acts vigorously upon the adjacent metal parts which in time become badly corroded. This electrolytic action also seems to remove the galvanizing from live metal parts before attacking the iron. A partial remedy for this rusting of live galvanized wire is painting.

This electrolytic effect is also seen to take place over strain insulators where the creepage distance is insufficient. This indicates that a creepage distance proportional to the conditions met must be secured to stop the flow of current around the outside of the insulators. The author concludes that, under fog conditions, the insulator surface exposed for creepage is insufficient in our present standard devices.

Another form of overhead electrolytic action noticed in electric railway work is caused by use of dissimilar metals in contact. Sulphuric acid and other fumes in the air, and ozone from a nearby ocean, are supposed to be the electrolytes that set up a local battery action at these points of contact. The logical remedy for this trouble is to use similar metal in contact. The paper then describes the troubles encountered in San Francisco due to these causes and the remedies which have been applied.

ON ELECTRIC railway construction in damp climates, and more or less in all climates, there is a light leakage of current from the trolley wire to the earth through the insulated supports. This flow of current if unchecked produces the same results as usually follow the electrolytic separation of water into oxygen and hydrogen. Oxygen is liberated at the positive end of the insulating device or the end nearest the trolley wire and attacks the metal immediately adjacent to the insulation. In the case of galvanized iron the zinc covering or galvanizing is soon removed and the iron is acted upon vigorously by the oxygen.

This effect is seen on the bolt or stud that fastens the trolley ear to the trolley hanger. The threaded lower end will be found

Manuscript of this paper was received May 20, 1915.

badly corroded, even though it had been smeared with thick oil on installation, while the rest of the bolt is less rusted. The explanation seems to be that a leaking current in passing from the exposed part of the bolt around the outside of the insulation to the metal body, by which the span wire is attached to the trolley wire, electrolytically disassociates the oxygen and hydrogen of the moisture present, the oxygen appearing at the positive pole and at once attacking the iron stud.

The electrolytic action is also seen in the film of green copper salt that spreads from the head of the brass ear over the lower surface of the cone to the iron hanger in cap and cone construction where exposed for long periods to moisture or salt spray, practically destroying its value as an insulator.

Iron oxide or rust, as it is usually called, occupies 2.2 times as much space as the iron from which it was formed and this continuous growth exerts a powerful lifting or heaving effect on the insulation above it. The progressive oxidation of iron results, in the case of the insulated bolt form of span wire insulation, in rupturing the enveloping material and gradually pressing the pieces further and further from the bolt, reducing the insulation resistance in proportion to the destruction of continuity of the enveloping insulating material, until the hanger becomes worthless as an insulator during wet weather. In the cap and cone form this oxydizing action results in splitting the cap in various directions and destroying its insulating value. In the cap this splitting of the insulating covering has been reduced by having the stud hot-dip galvanized before the insulation is pressed on it in the process of manufacture.

In the strain insulator this creepage-electrolysis effect is also seen. A globe strain, for example, exposed in a damp climate a few months as the only insulation between an uninsulated curve hanger and the pole (even in the case of a wooden pole) will show a heavy ring of iron rust around the shank of the eye on the end of the insulator toward the trolley wire, and a white zinc efflorescence on the end toward the pole while the interior upon crushing will be found to be clean and intact, its insulating conditions as good as ever and the galvanized surfaces bright and unimpaired. If time enough elapses this oxydation will split the spherical composition insulation open in cracks at the end toward the trolley wire. This seems to be due to simple electrical leakage over the three inches of surface of the insulator. It is too small to be measured with an ammeter and causes no hot poles nor opened circuit breakers.

With some forms of strain insulators this flow of current might be called "sneakage" as it occurs without outward sign through the interior of the device until the resistance has been broken down sufficiently to allow a clear path. In the case of a single insulator in the span wire there then occurs the phenomenon of a shocked lineman, a hot pole, a burned off support or occasionally a dead-grounded feeder at the power house. As a safeguard, three of these expensive insulators are sometimes seen used in series at each end of a span wire. This is probably the best method of increasing the creepage distance sought for provided the insulation is proof against "sneakage."

There is another interesting phenomenon connected with this leakage of current along span wires and guys. The current seems to pass off from the exterior of the live wire first removing electrolytically the galvanizing and then attacking the iron. In moist climates and especially where exposed to salt spray the "extra" or "double" galvanized strand when used where leakage current along it is possible rapidly becomes denuded of its zinc covering, gets red with rust, becomes pitted and quickly loses its tensile strength as if the wire being positive to the earth were discharging through the moisture of the atmosphere throughout its whole length. It may be claimed that action is due to insufficient galvanizing or to local action from impurities in the iron of the wire. That it is chiefly due to an electrolytic action is shown by considering guy wires put up nearby at the same time and used where little or no current could pass along them as in the case of an insulated drop guy between two wooden telephone poles attached below the crossarms on each pole. Here the galvanizing though unpainted was unaffected by the elements.

A partial remedy for this rusting of the live galvanized wire is painting as is seen by considering the end of a guy wire where it was painted at the wrap around the iron pole and beyond. Where painted it was not affected and was full size although corroded badly where unpainted. This corrosion also occurs when bare copper is used for guys or spans and is alive unless these wires are oiled or painted. That the trolley wire does not show effects of the action is supposed to be due to it being protected by a film of lubricant thrown upon it by the passing trolley wheels.

These points seem to teach that it is not only the high insulation puncture and flash-over tests of the trolley wire devices nor the crushing strength of the composition that are important

but the securing of a creepage distance proportional to the conditions met with so as to stop the flow of current around the outside of the insulating parts.

The substitution of glass or porcelain for the usually more or less fibrous and absorbent compounds in strain insulation prevents " sneakage " which is a distinct gain but still leaves the creepage along the surface. The gain is always being able to see the condition of the insulation in a properly designed glass or porcelain strain insulator, and in the reduced price originally, and for maintenance, has been considered in accounting for its popularity more than the danger from breakage of the relatively more brittle vitreous material. From this it would seem clear that the surface exposed for creepage is not enough under fog conditions in our present standard devices. Proper demand for neat; light weight parts has been complied with but we have not left enough distance between positive and negative sides to sufficiently protect the trolley supports from electrolytic action, necessitating that the hanger insulation be reinforced by a generous amount of permanent creepage distance in the span wire insulation—a creepage distance whose amount will not be reduced nor impaired by any electrolytic action in or around the strain insulator as it has been seen occurs on the underside of the cone in the hanger insulation when the surface is covered with a conducting film of metal or metallic salt from electrolytic action on the boss of the brass ear.

One factor is often overlooked that helps to neutralize the results of creepage—the insulation of the iron pole itself. Concrete is a fair insulator when dry but unless there is a layer of it under the pole the pole is not insulated as well as it could reasonably be. This concrete setting, as far as it goes, is a protective against the electrolytic injury to the wires and hangers above.

Leakage ground is not confined to iron poles but occurs on wooden poles on which there should always be a sufficient strain insulator in the span wire at either end. In the case of iron poles, if one strain insulator does not suffice two should be used, one about two feet from the trolley and one six feet from the pole. If two do not check the corrosion at the hanger and elsewhere on the span wire, insulators with more creepage distance over their insulated parts should be used as, for example, long wooden insulators. These latter, however, lack the tensile strength and the interlinking feature of the disk or cubical or

"goose egg" porcelain strain insulators. Disk insulators are heavier, more expensive and more liable to fracture from stones or wild trolley poles than the other kinds.

All galvanized iron strand intended for overhead use in connection with electric railway work is given by some companies two coats of linseed oil paint by dipping the wire, previously made up in coils of conveniently portable size, in a bath of paint, allowing the first coat to dry and dipping the wire a second time. It costs far less to apply the paint by immersion than with brushes by men on ladders or tower-wagons after the wire is in place. A paint giving the best results is the ordinary pole paint made with linseed oil as a vehicle and a metal oxide as a filler.

All joints made by the linemen in galvanized wires or cables should be painted at least one coat. The zinc of the galvanizing is scraped off the wires by the pliers, and unless painted, local action begins at once. All overhead parts should be painted before being installed and when poles are painted all wire and all cable joints, strain insulators, etc. within reach of the painters should be covered liberally with paint. This linseed oil harms nothing, is a good insulator and is the best known metal preservative. Local action will commence at once where the zinc covering has been abraded in handling the galvanized article. The covering of paint prevents this action from taking place by keeping the electrolyte from contact with the dissimilar metals in the injured surfaces.

There is another form of overhead electrolytic action met with in wires used in electric railway work. This is caused by the use of dissimilar metals in contact. Galvanized iron cables attached to the brass eyes of curve hangers, of spherical strain insulators etc. leads to rapid rusting off of the wire at the point of contact. The sulphuric acid found in the air of cities from the combustion of coal, from the escaping fumes of chemical works, the salt spray and ozone from a nearby ocean, etc. are thought to be the electrolytes that serve to start a local battery action. This action probably explains some of the corrosion at the thread of the hanger bolt that results in loose hangers in the ears.

The logical remedy for this is to use similar metals in contact—galvanized iron cable with galvanized iron parts and copper or bronze cable with brass parts. The local action will then be a minimum. Applying a heavy oil to the thread of the hanger stud when screwing it into the brass ear is a palliative by neutral-

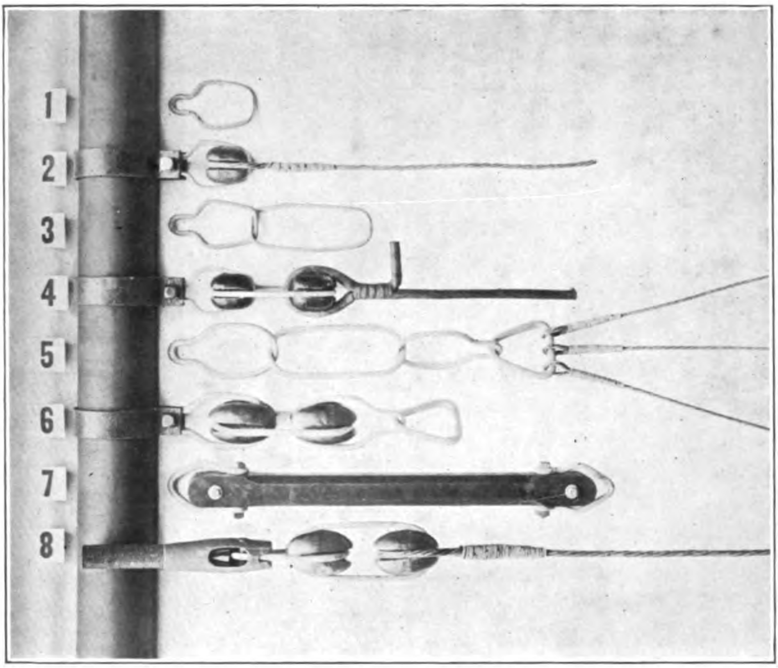
izing the electrolyte. As copper guy or span wires are more expensive than galvanized iron ones and do not withstand the blows from wild trolley poles as well, brass parts had better be replaced by galvanized iron ones for all overhead trolley work.

It is logical to believe and difficult to disprove that some of the wasting away of the iron pole at the top of the concrete setting, that sometimes seems to defy the painters and is often charged to the dogs, may be due in part at least to electrolysis, the leaking current passing from the iron of the pole along the damp surface of the ground toward the rails. Exceptionally rusty pole bases in spite of usual attention from the painters should justify investigations being made into the condition of the insulation in the span wire and at the ear.

In San Francisco these problems presented themselves early in electric railway experience and have been solved one after the other, producing not only improved conditions electrically but increased strength mechanically, reduced original cost, reduced maintenance cost and both greater safety for the workmen and greater rapidity of work. The first problem taken up was the electrolysis from the combination of the brass eye in the strain insulator and the galvanized iron strand. The galvanized strand corroded at an extraordinary rate in the brass insulator eye. This was remedied by having galvanized iron eyes used in the strain insulators in place of the brass eyes. Here there were two gains. The iron eye was stronger than the brass eye and the galvanized strand lasted longer in the iron eye than it did in the brass one.

The second problem was the failure of the strain insulators due to the heaving action of the iron oxide at the positive end of the insulator as already described.

For long periods during the summer months the heavy salt fog lay on the land near the ocean and kept the surfaces of these insulators bathed in moisture. The growing oxide forced the composition insulation open in numerous crevices and when the first winter rains came there were many hot poles reported on the system. The first rain storm of winter was a day to be dreaded by the linemen then. Between 1893 and 1901 every kind of strain insulator on the market was tried and found wanting—mica, composition, globe, Brooklyn etc. In 1901 a cheap glass later displaced by a porcelain cubical or "goose egg" strain insulator was adopted for all trolley work. Since then such a thing as a hot pole from a defective strain insulator has been un-



[FOSTER]

1. Single Link for Small Porcelain Insulator.
2. Single Link, Small Insulator and Span Wire Installed on Pole Band.
3. Double Link for Small Insulator.
4. Double Link, Small Insulators and No. 0000 Stranded Copper Feed-in or Tap-off Cable Used as a Span Wife.
5. Triple Link with Triangular Link for Large Insulators at Pull-Off or Strain Poles Used to Support Overhead Curves.
6. Same in Position on Pole.
7. Long Wood Strain Insulator Used on Fog-Exposed Locations.
8. Double Link and Large Insulators Used in Dead-Ending and Insulating 1,000,000 cir. mil Cable.

heard of during rain storms or at all. The creepage distance was no longer on the porcelain strains, insulators, in fact, nor half as long as on the globe strain, insulators that were displaced, but the creepage current did no harm to the vitreous insulator, was entirely on the exterior of the insulator and when the rain came there were no crevices or exposed fibrous surfaces to absorb moisture and facilitate leakage. The rain washed off the porcelain insulator and *improved* its insulating qualities if anything.

When there was a little or no fog a single porcelain insulator was used at each end of the span wire. Where the fog was heavier or there was feeding cable from a feeder used as a span wire two insulators were used in series. On particularly exposed lines along the cliffs around the Golden Gate even two of these and of a larger size did not suffice, and long wood strains had to be substituted, but that story will come later. Recently a state law has been passed requiring a strain insulator two feet from each trolley wire in the span wire and one at each end of every guy wire or cable. The result of this will be at least two porcelain strain insulators between the trolley wire and the pole everywhere.

The porcelain insulators referred to are of two sizes. To save the linemen's time and to improve the appearance of the overhead construction hot dip galvanized wrought iron welded links were made for use with the porcelain insulators. These links seem to be as durable as the insulators and were made in the following forms: single links for pole band attachment, double links for feeding at the pole or for feeder cable dead-ends, triple links with triangular bull-ring for curve pull-off poles. The links for the small insulators were made of $\frac{3}{8}$-in. and for the large ones of $\frac{1}{2}$-in. round Norway iron. The triangular bull-rings were made of $\frac{5}{8}$-in. steel.

The essential information relative to the two sizes of porcelain strain insulators referred to are as follows:

	Small	Large.
Diameter	$2\frac{3}{4}$ in.	$3\frac{1}{4}$ in.
Length	$3\frac{1}{2}$ in.	$\frac{5}{8}$ in.
Width of grooves	$\frac{1}{4}$ in.	5 in.
Weight	$1\frac{1}{8}$ lb.	3 lbs.
Crushing test	12,000 lb.	18,000 lb.
Flash over test-new, dry	10,000 volts.	30,000 volts.
Color	Dark brown.	Dark brown.
Cost each	$4\frac{3}{4}$ cents.	$23\frac{1}{2}$ cents.

The single link for the small insulator costs 10 cents and for the large one 15 cents. The smaller insulator is used in all spans and guys except those under extraordinary strain such as dead ends for trolley wires, 1,000,000-cir. mil cables etc. where the larger one is always found amply strong.

The method of use of these insulators ensures interlinking of the metal parts and maintaining of the conductor in the air in case of fracture of the porcelain which seldom occurs.

Where composition strain insulators are used, and from bitter experience the linemen have learned to know that their electrical sufficiency or insufficiency cannot be safely inferred from their external appearance, these men are accustomed to test the span wire before beginning work by making a rapid electrical connection from the trolley wire to the span wire with the opened handles of their connectors or gas tongs.

With porcelain insulators in the spans such tests are never required nor made by the men, as a glance at the insulator is all that is necessary. If the porcelain insulator is in place it must be intact and its insulation makes the span wire safe to handle without danger of it proving to be connected to the earth: Its external appearance is satisfactory evidence of its electrical sufficiency. The linemen also save the time formerly spent in testing the insulation of the span wires.

Further, there is little or no danger of the porcelain insulator failing while the men are working on its span wire, however old the insulator may be or however long it has been in service. A rifle bullet a blow from a stone thrown at it, or from a wild trolley pole are the only causes of injury to these insulators met with in our experience, and there are very few breakages indeed—hardly one-tenth of one per cent.

During the great San Francisco fire of 1906, all the expensive composition strain insulators, and in fact, all composition overhead parts such as caps, cones, one-piece hangers etc. swelled up under the heat and went out of business as electrical insulators whereas most of the cheap porcelain strain insulators passed through the ordeal safely and were gladly used again in the reconstruction, as the stocks of overhead material in our storeroom and those in the storerooms of all the local supply men had been destroyed.

The fact that these porcelain insulators in the span wires had withstood the flames enabled the main crosstown line to be put in service in less than 24 hours from the time the conflagration

subsided. The new trolley wire has used tied to the span wires with the temporary construction wire ties only, the porcelain strains at each end of the spans furnishing sufficient insulation between the trolley and the iron poles until the lacking hangers and ears could be obtained from outside the city.

From an ever expanding fourteen years experience with porcelain for all 500 volt d-c. electric railway strain insulator work, except extreme fog conditions, it has been proved in San Francisco practise, where there is neither snow, ice nor sleet and but little lightning, that porcelain is the best material for the purpose.

It is incombustible, nearly indestructible, invulnerable to atmospheric actions, requiring no original or subsequent preservative treatment, painting, testing or other attention, having higher compressive strength combined with small dimensions, protecting by the interlocking metal parts the conductors from falling, preserving the workmen from unexpected electrical shocks or waste of their time in determining the condition of the insulation by test, being cheaper to buy, costing nothing to maintain and enduring forever as good as when new.

The change in 1901 to porcelain as the exclusive material for strain insulator uses marked as important an advance in the art of keeping down the cost of maintaining the overhead construction of the trolley lines in San Francisco as the advent of the clinched ear in place of the soldered ear did a few years later.

The creepage distance from conductor to conductor on the smaller porcelain strain is only about $\frac{3}{4}$ of an inch. On our ocean exposed line skirting the Golden Gate we used the larger insulator on which the creepage distance was 2 inches. This did not prevent the rapid corrosion of the galvanized support cables.

In San Francisco fog practise, the size of the span wire has been increased from $\frac{1}{4}$ to 5/16 to $\frac{3}{8}$ inch and of guys from 5/16 to $\frac{3}{8}$ to $\frac{1}{2}$ inch in order to lengthen the life of these cables.
On this Cliff Line the overhead strand lasted only about two years. When one large porcelain did not answer, two in series were tried on this wood pole construction. Then wood strain insulators five inches between heads were tried only to have the iron heads corrode off rapidly. Wood strain insulators 15$\frac{3}{4}$ inches between heads really seemed to increase the life of the galvanized strand although the heads toward the trolley wire showed the characteristic electrolytic action and a heavy iron

oxide quickly accumulated over the sherardizing, the insulator heads toward the pole remaining normal.

We are now making homemade wood strain insulators 24 inches between conductors that are expected to ensure reasonable durability to these exposed "Extra" galvanized cables which, it should be stated, had been painted two heavy coats of linseed oil paint by dipping, previous to being put in place, as is done with all the strand of all sizes that is used in the overhead work.

These wood strain insulators last referred to are made of maple and boiled 24 hours and cooled off in linseed oil before being painted. They are 2 ½ in. thick, octagonal in section and pass a tensile strength test of 5000 pounds without showing any signs of distress.

It perhaps should be made clear that the porcelain insulator is subject to the same limitations as to protective power, according to creepage distance, as other forms of strain insulation. Where this distance is insufficient for the fog conditions met with, the conductor on the positive or trolley wire side of the insulator will be gradually weakened by the electrolytic action already described. This progressive deterioration is always visible, however, in the porcelain insulator construction, and the failing cable is usually replaced by a sound piece before the span or guy breaks. An additional insulator or one with longer creepage distance can be inserted at this time if the conditions seem to justify it.

In the absence of fog, this electrolytic weakening of the span does not become serious, and there are many cases in San Francisco outside the fire zone of 1906, where the original single small glass insulator per span, and original span wire installed thirteen years ago, are still in use and in satisfactory condition.

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PHYSICAL LIMITATIONS IN D-C. COMMUTATING MACHINERY

BY B. G. LAMME

ABSTRACT OF PAPER

In direct-current machines, there are a number of apparently distinct limitations, such as sparking at brushes, flashing at the commutator, burning and blackening of the commutator face, picking up of copper, etc. which, in reality, are very intimately related to each other. The principal object of the paper is to bring out such relationships and to show that all these actions are special cases of well known phenomena.

The theory of commutation is considered only in its relation to the e.m.fs. generated in the coils short circuited by the brush; and the limiting e.m.fs. per commutator bar and per brush are shown to be fixed principally by brush contact resistance. The effects of the negative coefficient of the contact resistance is also referred to briefly.

Flashing due to various causes is next taken up, and the relations between the maximum volts per bar and flashing conditions is indicated, both from test and general experience. Flashing due to various other causes, such as interrupting the circuit, etc. is also considered.

Burning and blackening of commutators, high mica, picking up of copper, etc. are treated in detail, and these actions are shown to be very closely related to the commutation limits derived in the earlier part of the paper.

Noise, vibration, etc. are also considered as limitations in design of d-c. apparatus. In approaching the ultimate design, these limitations become increasingly prominent.

Flickering of voltage and winking of lights are two well-known actions in direct-current practise. A simple explanation of the winking of lights (not original with the author) is given with the results of tests on a generator with well proportioned compensating windings in the pole faces. Apparently the difficulty is a fundamental one, and is liable to occur in all types of d-c. machines.

In conclusion, a brief chapter is given on design limitations as fixed by commutator peripheral speed. This applies particularly to large capacity high-voltage machines.

An appendix is added covering a method for determining the maximum capacity of d-c. machines in terms of the short circuit volts per commutator bar when the various constants in the machine are given certain limiting values. The results show that in large high-speed machines, the maximum capacity is considerably above present practise.

IN DIRECT-current commutating machinery there are many limitations in practical design which cannot be exceeded without undue risk in operating characteristics.

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Many of these limits are not sharply defined in practise, due, in many cases, to the impossibility of taking advantage of all the helpful conditions and of avoiding the objectionable ones. There are many minor conditions which affect the permissible limits of operation, which are practically beyond the scope of reliable calculation. Usually, such conditions are recognized, and allowance is made for them. It is the purpose of this paper to treat of some of the major, as well as minor, conditions which must be taken into account in advanced direct-current design. These are so numerous, and are so interwoven, that it is difficult to present them in any consecutive order.

Probably the most serious limitation encountered in direct-current electric machinery is that of commutation. This is an electrical problem primarily, but in carrying any design of direct-current machine to the utmost, certain limitations are found which are, to a certain extent, dependent upon the physical characteristics of materials, constructions, etc.

A second limitation which is usually considered as primarily an electrical one, namely, flashing, (and bucking) is in reality fixed as much by physical as by purely electrical conditions.

A third limitation is found in blackening and burning of commutators, burning and honeycombing of brushes, etc. These actions are, to a certain extent, electrical, but are partly physical and mechanical, as distinguished from purely electrical.

There are many other limiting conditions dependent upon speed, voltage, output per pole, quality or kind of materials used, etc. As indicated before, these cannot all be treated separately and individually, as they are too closely related to other characteristics and limitations.

Commutation and Commutation Limits

In dealing with the limits of commutation, it is unnecessary to go into the theory of commutation, except to indicate the general idea upon which the following treatment is based. This has been given more fully elsewhere,* and therefore the following brief treatment will probably be sufficient for all that is required in this paper.

In this theory it is considered that the armature winding as a whole tends to set up a magnetic field when carrying current, and that the armature conductors cutting this magnetic field

*A Theory of Commutation and Its Application to Interpolar Machines by B. G. Lamme, A. I. E. E. October, 1911.

will generate e.m.fs. just as when cutting any magnetic field. From consideration of the armature magnetomotive force alone, the flux or field set up by this winding would have a maximum value over those armature conductors which are connected to the brushes. If the magnetic conditions or paths surrounding the armature were equally good at all points, this would be true. However, with the usual interpolar spaces in direct-current machines, the magnetic paths above the commutated coils are usually of higher reluctance than elsewhere. However, whatever the magnetic conditions, the tendency of the armature magnetomotive force is to establish magnetic fluxes, and, if any field is established in the commutating zone by the armature winding, then those armature coils cutting this field will have e.m.fs. generated in them proportional to the field which is cut. As part of this armature flux is across the armature slots themselves, and part is around the end windings, both of which are practically unaffected by the magnetic path in the interpolar space above referred to, obviously, then no matter how poor the magnetic paths in the interpolar space above the core may be made, there will always be e.m.fs. generated on account of that part of the armature flux which is not affected by those paths. In the coils short circuited by the brushes, these e.m.fs. will naturally tend to set up local or short circuit currents during the interval of short circuit.

In good commutation, as the commutator bars connected to the two ends of an armature coil which is carrying current in a given direction, pass under the brush, the current in the coil itself should die down at practically a uniform rate, to zero value at a point corresponding to the middle of the brush, and it should then increase at a uniform rate to its normal value in the opposite direction by the time that the short circuit is opened as the coil passes from under the brush. This may be considered as the ideal or straight line reversal or commutation which, however, is only approximated in actual practice. This gives uniform current distribution over the brush face.

If no corrective actions are present, then the coil while under the brush tends to carry current in the same direction as before its terminals were short circuited. In addition, the short circuit current in the coil, due to cutting the armature flux, tends to add to the normal or work current before reversal occurs. The resultant current in the coil is thus not only continued in the same direction as before, but tends to have an increased value.

Thus the conditions at the moment that the coil passes out from under the short circuiting brush are much worse than if no short circuit current were generated. The reversal of the current would thus be almost instantaneous instead of being gradual as called for by the ideal commutation, and the resultant current reversed much greater than the work current alone. However, the introduction of resistance into the local circuit will greatly assist in the reversal as will be illustrated later. The ideal condition however, is obtained by the introduction of an opposing e.m.f. into the local short circuited path, thus neutralizing the tendency of the work current to continue in its former direction.

As this opposing e.m.f. must be in the reverse direction to the short circuit e.m.f. which would set up by cutting the armature magnetic field, it follows that where commutation is accomplished by means of such an e.m.f. it is necessary to provide a magnetic field opposite in direction to the armature field for setting up the commutating current. This may be obtained in various ways, such as shifting the brushes forward (or backward) until the commutated coil comes under an external field of the right direction and value, which is the usual practise in non-commutating pole machines; or a special commutating field of the right direction and value may be provided, this being the practise in commutating pole and in some types of compensated field machines. When the commutating e.m.f. is obtained by shifting the commutated coil under the main field, only average conditions may be obtained for different loads; whereas, with suitable commutating poles or compensating windings, sufficiently correct commutating e.m.fs. can be obtained over a very wide range of operation.

In practise, it is difficult to obtain magnetic conditions such that an ideal neutralizing e.m.f. is generated. However, the use of a relatively high resistance in the short circuited path of the commutated coil very greatly simplifies the problem. If the resistance of the coil itself were the only limit, then a relatively low magnetic field cut by the short circuited coil would generate sufficient e.m.f. to circulate an excessively large local current. Since such current might be from 10 to 50 times as great as the normal work current, depending upon the size of machine, it would necessarily add enormously to the difficulties of commutation whether it is in the same direction as the work current or is in opposition. To illustrate the effect of resistance, assume, for example, a short circuit e.m.f. in the commutated coil of two

volts, and also assume that a copper brush of negligible resistance short circuits the coil, so that the resistance of the short circuited coil itself practically limits the current to a value 20 times as large as the work current. Now replace this copper brush with one giving about 20 times as large a resistance (some form of graphite or carbon brush) then the total resistance in circuit is such that the short circuit current is cut down to a value about equal to that of the work current. This at once gives a much easier condition of commutation, even without any reversing field; while with such field, it is evident that extreme accuracy in proportioning is not necessary. Thus a relatively high resistance brush—or brush contact, rather—is of very great help in commutation; especially so in large capacity machines where the coil resistance is necessarily very low. In very small machines, the resistance of the individual armature coils has quite an influence in limiting the short circuit current.

It is in its high contact resistance that the carbon brush is such an important factor in the commutating machine. Usually, it is the resistance of the brush that is referred to as an important factor in assisting commutation. In reality, it is the resistance of the contact between the brush and commutator face which must be considered, and not that of the brush itself, which usually is of very much lower resistance, relatively. As this contact resistance or drop will be referred to very frequently in the following, and as the brush resistance itself will be considered in but a few instances, the terms "brush resistance" and "brush drop" will mean contact resistance and contact drop respectively, unless otherwise specified.

Short Circuit Volts per Commutator Bar. As stated before the armature short circuit e.m.f. per coil, or per commutator bar, is due to cutting a number of different magnetic fluxes, such as those of the end windings, those of the armature slots, and those over the armature core adjacent to the commutating zone. Each of these fluxes represent different conditions and distributions, and therefore the individual e.m.fs. generated by them may not be coincident in time phase. Therefore, the resultant e.m.f. usually may not be represented by any simple graphical or mathematical expression.

When an external flux or field is superimposed on the armature in the commutating zone, it may be considered as setting up an additional e.m.f. which may be added to, or subtracted from, the resultant short circuit e.m.f. due to the armature fluxes.

These component e.m.fs. are not really generated separately in the armature coils, for the external flux combines with part of the armature flux, so that the armature coil simply generates an e.m.f. due to the resultant flux. However, as part of the armature short circuit e.m.f. is generated by fluxes which do not combine with any external flux, as in the end winding, for instance, it follows that, to a certain extent, separate e.m.fs. are actually generated in the armature winding in different parts of the coil. For purposes of analysis, there are advantages in considering that all the e.m.fs. in the short circuited armature coil are generated separately by the various fluxes. A better quantitative idea of the actions which are taking place is thus obtained, and the permissible limitations are more easily seen. In the following treatment, these component e.m.fs. will be considered separately. As that component, due to cutting the various armature fluxes, will be referred to very frequently hereafter, it will be called the "apparent" armature short circuit e.m.f. per coil, or in abbreviated form, "the apparent short circuit e.m.f." In practise, on account of the complexity of the separate elements which make up the apparent short circuit e.m.f., it is very difficult, or in many cases, impossible, to entirely neutralize or balance it at all instants by means of an e.m.f. generated by an extraneous field or flux of a definite distribution. Therefore, it should be borne in mind that, in practise, only an approximate or average balance between the two component e.m.fs. is possible. With such average balance there are liable to be all sorts of minor pulsations in e.m.f. which tend to produce local currents and which must be taken care of by means of the brush resistance. Pulsations or variations in either of the component e.m.fs. are due to various minor causes, such as the varying magnetic conditions which result from a rotating open slot armature, from cross magnetizing and other distorting effects under the commutating poles, variations in air-gap reluctance under the commutating poles, pulsations in the main field reluctance causing development of secondary e.m.fs. in the short circuited coils, etc. Some of these conditions are liable to be present in every machine; some which would otherwise tend to give favorable conditions as regards commutation, are particularly liable to set up minor pulsations in the short circuit e.m.f. Therefore, brushes of high enough resistance to take care of the short circuit e.m.f. pulsations are a requisite of the present types of d-c. machines, and it may be assumed that there is but little

prospect of so improving the conditions in general that relatively high resistance brushes, or their equivalent, may be discarded. It is only on very special types of machines that low resistance brushes can be used.

With ideal or perfect commutation, the two component e.m.fs. in the short circuited coil should balance each other at all times. However, as stated before, this condition is never actually obtained, and the brush resistance must do the rest. With ideal commutation, the current distribution over the brush contact face should be practically uniform, and a series of voltage readings between the brush tip and commutator face should show uniform drops over the whole brush face. In most cases in practise however, such voltage readings will be only averages. For example, instead of a contact drop of one volt at a given point, the actual voltage may be varying from zero to two volts, or possibly from minus one volt to plus three volts. These pulsating e.m.fs. will result in high frequency local currents, which have only a harmful influence on the commutation and commutator and brushes. These pulsations may be assumed to be roughly related in value to the apparent short circuit volts generated by the armature conductor. In other words, the higher the apparent short circuit volts per conductor, the larger these pulsations are liable to be. As the currents set up by these pulsations must be limited largely by the brush contact resistance, it is obvious that there is a limit to the pulsations in voltage, beyond which the current set up by them may be harmful. A very crude practise, and yet possibly, the only fairly safe one, has been to set an upper limit to the apparent short circuit volts per bar, this limit varying to some extent with the conditions of service, such as high peak loads of short duration, overloads of considerable period, continuous operation, etc. Experience has shown that in commutating pole machines, the apparent short circuit voltages per turn may be as high as four to four-and-one-half volts, with usually but small evidence of local high frequency currents, as indicated by the condition of the brush face. If this polishes brightly, and the commutator face does not tend to " smut," then apparently the local currents are not excessive. However, in individual cases, the above limits have been very considerably exceeded in continuous operation, while, in exceptional cases, even with apparently well proportioned commutating poles, there has been evidence of considerable local current at less than four volts per bar.

The contact drop between brush and commutator with the usual brushes is about 1 to 1.25 volts. As is well known, this drop is not directly proportional to the current, but increases only slowly with very considerable increases in current density at the brush contact. For instance, with 20 amperes per sq. in. in a given brush, the contact drop may be one volt; at 40 amperes per square inch, it may be 1.25 volts, while at 100 amperes per square inch, it may be 1.4 volts, and, with materially higher currents, it may increase but little further. This peculiar property of the brush contact is, in some ways, very much of a disadvantage. For instance, if the local currents are to be limited to a comparatively low density, then necessarily the voltages generating such currents must be kept comparatively low. With the above brush contact characteristics, two volts would allow a local current of 20 amperes per square inch to flow, (there being one volt drop from brush to commutator and one volt back to the brush). If, however, the local voltage is three volts instead of two, or only 50 per cent higher, then a local current of possibly 150 to 200 amperes per square inch may flow, and this excessive current density may destroy the brush contact, as will be described later.

It may be assumed in general that the lower the apparent short circuit voltage per armature conductor, the lower the pulsations in this voltage are liable to be. Assuming therefore, as a rough approximation a 50 per cent pulsation as liable to occur, then, from the standpoint of brush contact drop, the total apparent voltage of the commutated coil in continuous service machines should not be more than 4 to $4\frac{1}{2}$ volts, which accords pretty well with practise. For intermittent services, such as railway, materially higher voltages are not unusual.

As the main advantage of the carbon brush is that it determines or limits the amount of short circuit current, it might be questioned whether such advantage might not be carried much further by using higher short circuit voltages and proportionately greater resistance. However, there are reasons why this cannot be done. The carbon brush is a resistance in the path of the local current, but it is also in the path of the work current. As the brush resistance is increased, the greater is the short circuit voltage which can be taken care of with a given limit in short circuit current, but at the same time, the loss due to the work current is increased. Decreasing the resistance of the brush contact increases the loss due to the short circuit current, but decreases

that due to the work current. Thus, in each individual case, there is some particular brush resistance which gives minimum loss. However, this may not always be the resistance desired for best commutation, from the operating standpoint, but these two conditions of resistance appear to lie fairly close together. Practise is a continual compromise on this question of brush contact resistance. In some machines, a low resistance brush is practicable, with consequent low loss due to work current. In other cases, which, to the layman, would appear to be exactly similar, higher resistance brushes give better average results. Thus one grade of carbon brush is not the most suitable for different machines unless they have similar commutating conditions. However, it is impracticable to design all machines of different speeds, types, or capacities so that they will have equal commutating characteristics. In non-commutating pole machines where only average commutating fluxes are obtainable, the resistance of the brush is usually of more importance than in the commutating pole type, for, in the latter, a means is provided for controlling the value of the short circuit current. However, advantage has been taken of this latter fact to such an extent in modern commutating pole machines, that the critical or best brush resistance has again become a very important condition of design and operation.

"Apparent" Short Circuit e.m.f. per Brush. The preceding considerations lead up to another limitation, namely, the total e.m.f. short circuited by the brush. This again may be considered as being made up of two components,—the apparent short circuit e.m.f. per bar times the *average* number of bars covered by the brush, hereafter called "The apparent short circuit e.m.f. per brush"; and the e.m.f. per bar generated by the commutating field, times the average number of bars covered by the brush.

As has been shown, ordinary carbon brushes can short circuit 2 to 2½ volts without excessive local current. Obviously, if the resultant e.m.f. generated in all the coils short circuited by the brush,—that is, the resultant of the short circuit e.m.fs., due to both the armature and the commutating field is much larger than 2½ volts, large local currents will flow. Therefore, in a commutating pole machine, for instance, the strength of the commutating pole field should always be such that it also neutralizes the total short circuit e.m.f. across the brush within a limit represented by the brush contact drop, in order to keep

within the limits of permissible local currents. With very low resistance brushes, the proportioning of the commutating field for neutralization of the apparent brush e.m.f. would have to be much closer than with higher resistance brushes. Moreover, not only should this e.m.f. generated by the commutating flux balance the total short circuit voltage across the brush within these prescribed limits, but these limits should not be exceeded anywhere under the brush.

It might be assumed that if there is a pulsation of two volts per coil, for instance, then the total pulsation would be equal to this value times the average number of coils short circuited. However, this in general is not correct, as the e.m.f. pulsations for the different coils are not in phase, and their resultant may be but little larger than for a single coil.

Based upon the foregoing considerations, the limiting values of the apparent brush e.m.f. may be approximated as follows: Assume ordinary carbon brushes with 1 to $1\frac{1}{4}$ volts drop with permissible current densities—that is, with 2 to $2\frac{1}{2}$ volts opposing action as regards local currents. Also, assume, for example, an apparent brush short circuit e.m.f. of 5 volts, with brush resistance sufficient to take care of $2\frac{1}{2}$ volts. Then the total e.m.f. due to the commutating flux need not be closer than 50 per cent of the theoretically correct value, with permissible local currents. This is a comparatively easy condition, for it is a relatively poor design of machine in which the commutating pole strength cannot be brought within 50 per cent of the right value. Assuming next, an apparent brush e.m.f. of 10 volts, then the commutating pole must be proportioned within 25 per cent of the right value. In practise, this also appears to be feasible, without undue care and refinement in proportioning the commutating field. If this machine never carried any overload, this 25 per cent approximation would represent a relatively easy condition, for experience has shown that proportioning within 10 per cent is obtainable in some cases, which should allow an apparent brush e.m.f. of 25 volts as a limit. However, experience also shows that this latter is a comparatively sensitive condition, which, while permissible on short peak loads, is not satisfactory for normal conditions. Where such close adjustment is necessary to keep within the brush correcting limits, any rapid changes in load are liable to result in sensitive commutating conditions, for the commutating pole flux does not always rise and fall exactly in time with the arma-

ture flux, and thus momentary unbalanced conditions of possibly as high as 10 or 12 volts might occur with an apparent brush e.m.f. of 25 volts. Also, very slight saturation in the commutating pole magnetic circuit may have an unduly large influence on unbalancing the e.m.f. conditions. In other words, the apparent brush short circuit and neutralizing e.m.fs. must not be unduly high compared with the permissible corrective drop of the brushes. Experience shows that an apparent e.m.f. of 10 volts across the brush in well designed commutating pole machines is usually very satisfactory, while, in occasional cases, 12 to 13 volts allow fair results on large machines, and, in rare cases, as high as 15 to 18 volts has been allowed on small machines at normal rating. However, overloads, in some cases, limit this permissible apparent brush voltage. As a rule, 30 volts across the brush on extreme overload is permissible, but, usually this is accompanied by some sparking, usually not of a very harmful nature if not of too long duration. Under such overload conditions, doubtless unbalancing of three volts or more may be permissible, and thus, with 30 volts to be neutralized, this means about 90 per cent theoretically correct proportioning of the commutating pole flux. Cases have been noted where as high as 35 to 40 apparent brush volts have been corrected by the commutating pole on heavy overloads with practically no sparking. This, however, is an abnormally good result, and is not often possible of attainment. Obviously, with such high voltages to be corrected, any little discrepancies in the balancing action between the various e.m.fs. are liable to cause excessive local current flow.

Incidentally, the above indicates pretty clearly why d-c. generators are liable to flash viciously when dead short circuited. The ordinary large capacity machine can give 20 to 30 times rated full load current on short circuit. If this large current flows, then, neglecting saturation, the armature short circuit e.m.f. across the brush will be excessive. Assuming, for instance, a 10-volt limit for normal rating, then with only ten times full load current, the apparent short circuit e.m.f. would be 100 volts. The commutating pole, in the normal construction, does not have flux margin of 10 times before high saturation is reached, and in consequence, it may neutralize only 50 to 60 volts of the 100. Therefore a resultant actual e.m.f. of possibly 40 volts must be taken care of by the brushes. This means an enormous short circuit current in addition to

the 10 times work current. Vaporization of the copper and brushes occurs and flashing results, as will be described more fully in the treatment of flashing limits.

Brush contact drops of 1 to 1.5 volts have been assumed in the preceding, and certain limits in the apparent short circuit e.m.f. based on these drops, have been discussed. However, the conditions may be modified to a considerable extent by effects of temperature upon the brush contact resistance. Usually it has been assumed that the well known decrease in contact resistance of carbon and graphite brushes with increase in temperature, is in some ways related to the negative temperature coefficient of carbon and graphite. The writer has been among those who advanced this idea, but later experience, based upon tests, has shown that the reduced drop with increase in temperature does not necessarily hold any relation to the negative temperature coefficient of the carbon brush itself, for similar changes in the contact drop have been found with materials, other than carbon, which actually had, in themselves, positive temperature coefficients. Moreover, in some tests, the changes in contact resistance with increase in temperature have proved to be much greater in proportion than occurs in the carbons themselves. In some cases, the measured drops with temperature increases of less than 100 deg. cent. decreased to one-half or one-third of the drops measured cold.

Obviously, these decreased contact resistances or drops may have a very considerable effect on the amount of local current which can flow and, therefore, in such case the foregoing general deductions, should be modified accordingly. However, the results are so affected by the oxidation of the copper commutator face, and other conditions also more or less dependent upon temperature, that, as yet, no definite statement can be made regarding the practical effects of increase in temperature except the general one that the resistance is usually lowered to a considerable extent. Apparently, oxidation of the copper face tends toward higher contact resistance. Ofttimes, "sanding off" the glaze tends to give poorer commutation. The above points to one explanation of this.

Assuming any desired limits for the apparent e.m.fs., such as 4 to $4\frac{1}{2}$ volts per commutator bar, it is possible to approximate by calculation the limiting capacities of generators or motors in terms of speed, etc. Appendix I shows one method of doing this. In the writer's experience, a number of machines have been

carried up to about the limits derived in the appendix, and the practical results were in fair accord with the calculations. In general, it may be said that in large machines, the upper limits of capacity in terms of speed, etc. are so high that they do not indicate any great handicap on future practise.

In the foregoing, the limits for the apparent short circuit e.m.f. per bar and per brush have been based upon the brush contact resistance. However, it may be suggested that something other than the brush contact resistance might be used for limiting the local current, and thus the commutating limits might be raised. For instance, an armature winding could be completely closed on itself, with high resistance leads carried from the winding to the commutator bars. Each of such leads would be in circuit only where the brushes touched the commutator bars. Thus there could be very considerable resistance in each lead without greatly increasing the total losses; and, unlike the brushes, each lead would be in circuit only for a very small proportion of the time.

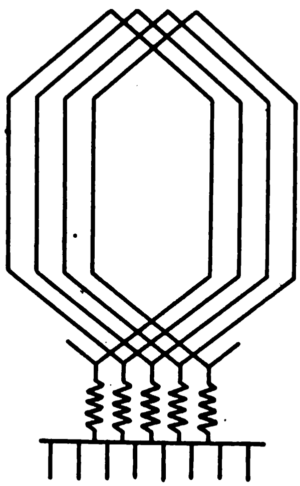

FIG. 1

About 10 years ago, the writer designed a non-commutating pole d-c. turbo-generator with such resistance leads connected between the winding and the commutator. The leads were placed in the armature slots below the main armature winding. The idea was to have enough resistance in circuit with the short circuited coils that the brushes at no load could be thrown well forward into a field flux sufficient to produce good commutation at heavy load, even if very low resistance brushes were used. Tests of this machine showed that the non-sparking range, with the brushes shifted either forward or back of the neutral point was very much greater than in an ordinary machine. In this case, it developed that the leads were of too high resistance for practical purposes, as the armature ran too hot, the heat-dissipating conditions in a small d-c. turbo-armature not being any too good at best. These tests however, indicate one possibility in the way of increasing the present limits of voltage per bar and volts across the brush. Moreover, such resistances can have a positive temperature coefficient of resistance, instead of the

negative one of the carbon brushes and contacts. Also, the corrective action in limiting local currents would vary directly with the current over any range, and not reach a limit, as in carbon brushes.

Considerable experience with resistance leads in d-c. operation has also been obtained in large a-c. commutator type railway motors, designed for operation on both a-c. and d-c. circuits. Apparently these leads have a very appreciable balancing action as regards division of current between brush arms in parallel. With but few brushes per arm, it appears that very high current densities in the brushes can be used without undue glowing or honeycombing. Presumably the reduction in short circuit current, when operating on d-c., also has much to do with this. Some special tests were made along this line, and it was found that a very low resistance in the leads, compared with that which was best for a-c. operation, was sufficient to exert quite a decided balancing between the brush arms.

With properly proportioned resistance leads it should be possible to use very low resistance brushes, and relatively high current densities. Advantage of this might be taken in various ways. There may prove to be serious mechanical objections to such arrangements. However, if the objections are not too serious, the use of resistance leads in this manner may be practised at some future time as we approach more extreme designs.

Flashing

One of the limits in commutating machinery is flashing. This may be of several kinds. There may be a large arc or flash from the front edge of the brush, which may increase in volume until it becomes a flash-over to some other part of the machine. Again, a flash may originate between two adjacent bars at some point between the brush arms, and may not extend further, or it may grow into a general flashover. Different kinds of flashes may arise from radically different causes, some of which may be normally present in the machine, while others may be of an accidental nature.

Whatever the initial cause, the flash itself means vaporized conducting material. If the heat developed by or in this vapor arc is sufficient to vaporize more conducting material—that is, generate more conducting vapor—then the arc or flash will grow or continue. Thus, true flashing should be associated with vaporization, and, in many cases, in order to get at the initial

cause of flashing, it is only necessary to find the initial cause of vaporization.

Arcs Between Adjacent Commutator Bars. This being one of the easiest conditions to analyze, it will be treated first, especially as certain flashing conditions are dependent upon this.

A not uncommon condition on commutators in operation is a belt of incandescent material around the commutator, usually known as "ring fire." This is really incandescent material between adjacent bars, such as carbon or graphite, scraped off the brush faces usually by the mica between bars. As the mica tends to stand slightly above the copper, due to less rapid "wear," its natural action is to scrape carbon particles off the brush. These particles are conducting and if there is sufficient voltage, and current to bring them up to incandescence, this shows as a streak of fire around the commutator. In many cases, by its different intensities around the commutator, this ring fire shows plainly the density of the field flux, or e.m.f. distribution around the machine. It is practically zero in the commutating or neutral zone, and shows plainly under the main field. In loaded machines, this often indicates roughly the flux distortion. In machines which act alternately as motors and generators, as in reversing mill work, the point of highest incandescence shifts forward or backward over the commutator, depending upon the direction of field distortion.

In undercut commutators (those with mica cut below the copper surface) this ring fire is also observable at times, due to conducting particles in the slots between bars. Usually such particles consist of carbon or graphite, as already stated, but particles of copper may also be present. Also, oil or grease, mixed with carbon, will carbonize under incandescence, and will thus add to the ring fire. Often when a commutator is rubbed with an oiled cloth or wiper, ring fire will show very plainly, and then gradually die down. The burning oil exaggerates the action, and also, the oil itself may enable a conducting coating to adhere to the mica edges, thus starting the action, which disappears when the oil film is burned away. However, when the oil can penetrate the mica, the incandescence may continue in spots and at intervals, the mica being calcined or burned away so that it gradually disppears in spots. This is the action usually called "pitting", which experience has shown to be almost invariably caused by conducting material in the mica, such as carbonized oil, carbonized binding material, copper and carbon particles which have been carried in with the oil, etc.

This ring fire is not always a direct function of the voltage between bars, although, under exactly equivalent conditions of speed, grade of brushes, etc., it is closely allied with voltage conditions. In high voltage machines, usually hard high-resistance brushes are used, which tend to give off the least carbon in the form of particles; while in low voltage machines, soft, low-resistance brushes, with a good percentage of graphite in them, are common, and these naturally tend to coat the mica to a greater extent.

Under extreme conditions, this ring fire may become so intense locally that there is an actual arc formed between two adjacent bars, due to vaporization of the copper. This may show in the form of minute copper beads at the edge of the bar, or minute "pits" or "pockets" may be burned in the copper next to the mica. In extreme cases, where the voltage between bars is sufficient to maintain an arc, conical shaped cavities or holes may be burned in the copper. In such cases, the arc is usually explosive, resembling somewhat a small "buck-over." An examination of the commutator will show melted-out places, as in Fig. 2. Part of the missing copper has been vaporized by the arc, while part may have become so softened or fused that it is thrown off by centrifugal force. Experience shows that sometimes these explosives arcs grow into general flashes, while at other times, they are purely local.

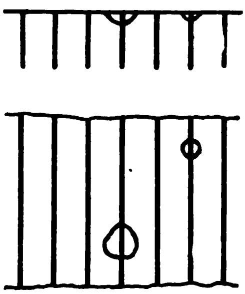

Fig. 2

An extended study was made of such arcs to determine the conditions which produced them. Also, numerous tests were made, the results of which are given below.

It was determined first that these explosives arcs between adjacent bars were dependent, in practically all cases, upon a fairly high voltage between bars. This was reasonable to expect, but it was found that the voltage between bars which would produce arcs in one case, would not do so in another. Apparently there were other limiting or controlling conditions. It developed that the resistance of the armature winding between two adjacent bars has much to do with the arc. Apparently an excessive current is necessary to melt a small chunk out of a mass of good heat-conducting material like a large copper commutator; and also, a certain amount of time is required to bring it up to the

melting point. Therefore, both time and current are involved, as well as voltage. A series of tests was made to determine some of the limiting conditions.

The commutator of a small machine (about 20 kw., high speed) was sprinkled with iron filings, fine dust, etc. during several days' operation under various conditions of load, field distortion, etc. Such dust, whether conducting or not, apparently would not cause arcing between bars. Graphite was finally applied with a special "wiper," and with this, small arcs or flashes could be produced at 50 to 60 volts maximum between commutator bars. It soon became evident that this was too small a machine from which to draw conclusions. Then numerous other much larger generators were tested. A slow-speed engine type generator of 200-kw. capacity at 250 volts, was speeded up to about double speed, in order to obtain sufficiently high e.m.f. between commutator bars. With a clean commutator nothing was obtained at 40 volts maximum per bar. The commutator was then wiped with a piece of oily waste which had been used to wipe off other commutators. Arcs then occurred repeatedly between commutator bars, although all such arcs were confined to adjacent bars and there were no actual flashovers from brush holder to brush holder. Moreover, the arcs always appeared to start about midway between brush arms or neutral points, and lasted only until the next neutral point was reached. Quite large pits or cavities were burned in the bars next to the mica, as shown in Fig. 2. some of these being possibly $\frac{1}{4}$ inch in width, and 1/16 inch deep or more at the center. This indicated excessively large currents. These arcs would develop at about 32 to 34 volts between bars, and they were very vicious (explosive) above 35 volts.

Still larger machines were tested with various speeds, voltage between bars, etc. It was found that, as a rule, the larger the machine—or rather, the lower the resistance of the armature winding per bar—the lower would be the voltage at which serious arcing would develop. In these tests, it was found that graphite mixed with grease gave the most sensitive arcing conditions.

In these various tests, no arcing between bars was developed in any case at less than 28 volts maximum, while 30 volts was approximately the limit on many machines. However, the results varied with the speed. Apparently it took a certain time to raise the incandescent material to the arcing point and to build up a big arc. Therefore, the duration of the possible arcing period appeared to be involved. If this were so, then a higher

voltage limit for a shorter time should be possible with the same arcing tendency. Also, if this were the case, then with 30 volts maximum, for instance, between commutator bars with an undistorted field flux, the arcing should be the same as with a somewhat higher voltage with a highly distorted narrow peaked field. In other words, the limiting voltage between bars on a loaded machine might be somewhat higher than on an unloaded machine. This was actually found to be the case, the difference being from 10 per cent to 15 per cent in several instances. This, however, depended upon various limiting conditions such as the actual period within which the arc could build up to a destructive point, etc.

One very interesting case developed which apparently illustrated very beautifully the effects of lengthening or shortening the period during which the arc could occur. A high-speed, 600-volt generator of a motor-generator set was speeded up about 60 per cent above normal. Even at normal speed this was a rather high-frequency machine, so that the period of time for a commutator bar to pass from neutral point to neutral point was very short. At the highest speed the graphite-grease was used liberally on the commutator, but without causing arcing, even when the voltage was raised considerably higher than usually required for producing arcs between bars in other machines of similar size. Neither was there much ring-fire at the highest speed with normal voltage. Finally, after an application of graphite, without forming arcs or unusual ring-fire, the speed was reduced gradually with normal voltage maintained. The ring-fire increased with decrease in speed, until at about normal speed, it was so excessive that the on-lookers expected an explosion of some sort. However, the voltage was now below the normal arcing point and nothing happened. At still lower speed, but with reduced voltage on account of saturation, the ring-fire gradually decreased. Apparently at the very high speeds, the time was too short for the ring-fire to reach its maximum; while with reduction in speed, even with somewhat reduced voltage, the ring-fire increased to a maximum and then decreased. This test was continued sufficiently to be sure that it was not an accidental case. Only a certain combination of speed, frequency, voltage, etc. could develop this peculiar condition, and it was purely by accident that this combination was obtained, for the result was not foreseen in selecting the particular machine used.

A summation of these and other tests led to the conclusion that there were pretty definite limits to the maximum volts per bar, beyond which it was not safe to go. These limits however, involved such a number of conditions that no fixed rule could be established, and apparently, the designer has to use his judgment and experience to a certain extent, if he works very close to the limits. The grades and materials of the brushes, the thickness of the mica, flux distortion from overloads, etc. must be taken into account. For instance, the above tests were made on machines with 1/32-inch mica between bars. This thickness is fixed, to a great extent, in non-undercut commutators, by conditions of mica wear, as will be referred to later. But with undercut commutators, thicker mica can be used, and, while the gain in permissible safe voltage between bars is not at all in proportion to the mica thickness, yet it is enough to deserve consideration.

The general conclusions were that with 1/32-inch mica, large current machines would very rarely flash with 28 volts *maximum* between bars; while with moderate capacities, 30 volts is about the lower limit; and with still smaller machines, 100 kw. for example, this might be as high as 33 to 35 volts, the limit rising to 50 or 60 volts with very small machines.

Of course, the brush conditions have something to do with the above limits, and many exceptions to these figures will be found in actual practise. Many machines are in daily service which are subject to more or less ring-fire, but which have never developed trouble of any sort, and doubtless never will. Apparently, ring-fire in itself is not harmful, as a rule. It is only where it starts some other trouble that it may be considered as actually objectionable.

The above limiting figures are interesting when compared with the voltages necessary to establish arcs in general. An alternating arc through air will not usually maintain itself at less than some limiting voltage such as 20 to 25 volts, corresponding to peak values of 28 to 35 volts. Moreover, an arc formed between the edges of two insulated bodies, such as adjacent commutator bars, will naturally tend to rupture itself due to the shape of its path. Furthermore, the resistance and reactance of the short circuited path, while comparatively low in large machines, will tend to limit the voltage which maintains the arc. In small machines with relatively high internal drops in the short circuited coils, the current will not reach a

commutator vaporizing value unless the initial voltage between bars is comparatively high, and usually the explosive actions are relatively small, and, in many cases, no serious arcs will develop at all. Obviously, the less the local current can increase in the case of short circuits between adjacent bars, the higher the voltage between bars can be, without danger. In machines having *inherent constant current characteristics*, very high voltages between adjacent commutator bars are possible without serious flashing or burning. In consequence, from the flashing standpoint, constant current machines can be built for enormously high terminal voltages, compared with constant potential machines. This is a point which is very commonly overlooked in discussing high-voltage d-c. machines.

Coming back to the subject of arcs between commutator bars, these are more common than is usually supposed, for, in many cases, the operating conditions are such that these arcs, if very small, or limited, will show no visible evidence. Only very minute particles of copper may be vaporized. However, these minute arcs may sometimes lead directly to more serious flashing. If, for instance, they occur in proximity to some live part of the machine, such as an over-hanging brush holder which is at a considerable difference of potential from the arcing part of the commutator, the conducting vapor may bridge across and start a big arc or flash. In one instance, which the writer has in mind, a very serious case of trouble occurred in this way. This was a very large capacity 250-volt, low-speed, generator, in which the maximum volts per bar were not unduly high. When taking the saturation curve in the shop test, this machine "bucked" viciously several times, apparently without reason. An investigation of the burning indicated a possible source of trouble. The brush holder arms or supports to which the individual holders were attached, were located over the commutator about midway between neutral points, and, about one inch from the commutator face. This was not the normal position of the brush arms, as a temporary set of holders was being used for this test. It was noted that just before the flashovers occurred, considerable ring-fire developed. The conclusion was drawn from all the evidence that could be obtained, that a small arc had formed between bars that had reached to the brush arms, thus short circuiting a high enough voltage to draw a real flash. This happened not once but several times. The proper holders

were then applied, which put the brush arms in a much less exposed position, and not a single flashover occurred in all the subsequent tests and operation. In another case, a large synchronous converter carrying full load on shop test flashed over a number of times, apparently without sufficient cause. The commutation was perfect, as evidenced by the fact that there was no perceptible sparking. The maximum voltage between bars was comparatively low. At first the flashovers were blamed on drops of water from the roof of the building, but this theory was soon disproved. An examination of the brush holders showed that certain live parts, fairly close to the commutator, were at a considerable difference of potential from the nearest part of the commutator. There was but little ringfire on the commutator, and therefore, minute arcs at first were not blamed for the trouble. A modified brush holder was tried however, with a view to decreasing the high difference of potential between the live parts. All flashing then disappeared and no trouble of this sort was ever encountered in a large number of duplicate machines brought through afterwards. Both the above cases should be considered as abnormal, and they have been selected simply as examples of what small arcs between bars may do. These two cases do not in themselves constitute a proof of this action, but they serve to verify other evidences which have been obtained.

In view of the fact that small arcs of a non-explosive sort may form at voltages considerably lower than the limits given in the preceding part of this paper, it should be considered whether such small arcs can cause any trouble if no other live parts of the machine are in close proximity. One case should be considered, namely, that of other commutator bars adjacent to the arc. When conducting vapor is formed by the first minute arc, this vapor in spreading out may bridge across a number of commutator bars having a much higher total difference of potential across them than that which caused the initial arc. Assume, for instance, a very crowded design of high-voltage commutator. In some cases, in order to use high rotative speeds, without unduly high commutator peripheral speed, the commutator bars are sometimes made very thin and the volts per bar very high, possibly up almost to the limit. Assuming a thickness of bar and mica of 0.2 inch (or 5 bars per inch) and a maximum volts per bar of 25, then there is an e.m.f. of 125 volts *per inch* circumference of the commutator. In such

case, a small arc between two bars may result in bridging across a comparatively high voltage through the resulting copper vapor. Therefore, when considering the possible harmful effects of minute arcs, the volts per inch circumference of the commutator should be taken into consideration. The writer observed one high-voltage commutator which flashed viciously at times, apparently without "provocation." The only explanation he could find was that the vapor from little arcs resulting from ringfire was sufficient to spread all over the commutator, the bars being very thin and the voltage per bar very high. However, difficulties from this cause have not yet become serious, probably because no one has yet carried such constructions to the extreme, in practical work.

High voltage between commutator bars may result in flashing due to other than normal operating conditions. Excessive overloads may give such high voltages per armature coil or per commutator bar, immediately under the brush, that the terrific current rush will develop conducting vapors under the brush, which appear immediately in front of the brushes, as such vapors naturally are carried forward by rotation of the commutator. This short circuit condition under the brush has already been referred to when treating of commutation limits. It was shown then that an inherent short circuit voltage of 4 to 4½ volts is permissible in good practise. Immediately under the commutating pole this voltage is practically neutralized by the commutating pole field, but immediately ahead or behind the pole it is not neutralized usually, except to the extent of the commutating pole flux fringe. Thus, the resultant voltage between two bars a little distance ahead of the brush, is liable to be considerably higher than under the brush. Assuming, for instance, 3½ volts per bar, due to cutting the resultant field just ahead of the brush, then with 10 times full load current, for example, there would be 35 volts between bars, and this is liable to be accompanied by highly conducting vapor formed by the excessive current at the brush contact, this vapor being carried forward by rotation of the commutator. Here are the conditions for a flash, which may or may not bridge across to some other live part. If the current rush is not too great, this flash will usually appear only as a momentary blaze just in front of the brush. In many cases, if this blaze or heavy arc were not allowed to come in contact with, or bridge between, any parts having high difference of potential, it would not be

particularly harmful. In case of "dead short circuiting" of large moderately high-voltage machines where the current can rise to 25 or 30 times normal, it is astonishing how large such arcs or flashes may become, and to what distances they will reach. The arc will sometimes go in unanticipated directions. The conducting vapor may be deflected by magnetic action and by air drafts. Shields or partitions will sometimes produce unexpected results, not necessarily beneficial. Unless such shields actually touch the commutator face so that conducting vapor cannot pass underneath them, the vapor that does pass underneath may produce just as harmful results as if the shields were not used. Trying to suppress such arcs by covers or shields is very much the case of damming a river at the wrong end in order to prevent high water.

From the preceding considerations it would appear that a compensated direct-current machine should have some advantages over the straight commutating-pole type in case of a severe short circuit. With the lesser saturation in the commutating pole circuit due to the lower leakage, the apparent armature short circuit e.m.f. will usually be better neutralized under extreme load conditions, and thus there will be lower local currents in the brush contacts. In addition, the armature flux will be practically as well neutralized behind and ahead of the brush, as it is under the brush, so that, with ten times current as in the former example, there may be only a low e.m.f. per bar ahead of the brush, instead of the 35 volts for the former case. Obviously, the initial flashing cause, and the tendency to continue it ahead of the brush, will be materially reduced. The compensating winding is therefore particularly advantageous in very high voltage generators, in which the bars are usually very thin and the maximum volts per bar are high.

There is a prevailing opinion that when a circuit breaker opens on a very heavy overload or a short circuit, flashing is liable to follow from such interruption of the current. In some cases, this may be true. However, when a breaker opens on a short circuit, it is difficult for the observer to say whether both the opening of the breaker and the flash are due to the excessive momentary current, or one is consequent to the other. The short circuit, if severe, will most certainly cause more or less of a flash at the brush contacts by the time the breaker is opened, and if this flash is carried around the commutator, or bridges

across two points of widely different potentials, then it is liable to continue after the breaker opens, and thus gives the impression that the flashing followed the interruption of the circuit. In railway and in mine work in particular, a great many flashes which are credited to overloads are primarily caused by partial short circuits on the system, or "arcing shorts," which are extinguished as soon as the main breakers are opened, so that but little or no evidence of any short circuit remains. Such a partial short circuit however, may be sufficient to open the generator circuit and to cause a flash at the same time. Not infrequently, such flashes are simply credited to opening of the breakers.

There are other conditions, however, where a flash is liable to result directly from opening the breaker on heavy overload. If, as referred to before, the apparent short circuit e.m.f. per brush on heavy overload is from 25 to 35 volts, then if the armature magnetomotive force could be interrupted suddenly, with a correspondingly rapid reduction in the armature flux, while the commutating field flux does not die down at an equally rapid rate, then momentarily, there will be an actual short circuit voltage of a considerable amount under the brushes which may be sufficient to circulate large enough local currents to start flashing. With commutating pole machines, this condition may result from the use of solid poles and solid field yokes. Laminated commutating poles are sometimes very much of an improvement. However, the yokes of practically all direct current machines are of solid material, and thus tend to give sluggishness in flux changes. The above explains why non-inductive shunts, or any closed circuits whatever, are usually objectionable on commutating poles or their windings.

In non-commutating pole machines, where the brushes are liable to be shifted under the main field magnetic fringe in order to commutate heavy loads, flashing sometimes results, when such heavy overload is interrupted.

Also, if the rupture of the current is very sudden, there will be an inductive "kick" from the collapse of the armature magnetic field. This rise in voltage sometimes is sufficient to start a flash, especially in those cases where flashing limits are already almost reached.

In synchronous converters, the conditions are materially different from d-c. generators as regards flashing when the load is suddenly broken. In such machines, the flash is liable

to follow the opening of the breaker, if simply a heavy overload is interrupted. This is possibly more pronounced in the commutating pole machine than in the non-commutating pole type. In a commutating pole converter, the commutating pole magnetomotive force is considerably larger than the resultant armature magnetomotive force, under normal operating conditions, but is much smaller than the armature magnetomotive force considered as a straight d-c. or a-c. machine. Normally the commutating pole establishes a commutating field or flux in the proper direction in the armature. However, if, for any reason, the converter becomes a motor or a generator, even momentarily, the increased magnetomotive force of the armature may greatly exceed that of the commutating pole, so that the commutating pole flux will be greatly increased, or it may be greatly reduced, or even reversed, depending upon which armature magnetomotive force predominates.

The above is what happens when a synchronous converter hunts, and under the accompanying condition of variable armature magnetomotive force, the commutating pole converter, with iron directly over the commutating zone, is liable to show greater variations in the flux in the commutating zone than is the case in the non-commutating pole converter. Experience has shown that when a synchronous converter carrying a heavy overload has its direct-current circuit suddenly interrupted, it is liable to hunt considerably for a very short period, depending upon the hunting constants of the individual machine and circuit. Apparently, all converters hunt to some extent with such change in load. This hunting means wide variations in the commutating pole flux with corresponding sparking tendencies. For a "swing" or two, this sparking may be so bad as to develop into a flash. Thus the flash follows the interruption of the circuit.

Curiously, the most effective remedy for this condition is one which has proved most objectionable in d-c. machines, namely, a low-resistance closed electric circuit surrounding the commutating pole. The primary object of this remedy is not to form a closed circuit around the commutating field, but to obtain a more effective damper in order to minimize hunting. In a paper presented before the Institute several years ago,* the writer showed that the ideal type of cage winding for damp-

*Interpoles in Synchronous Converters, by B. G. Lamme and F. D. Newbury, A. I. E. E., TRANS. 1910.

ing synchronous converters, namely, that in which all circuits are tied together by common end rings, was not suitable for commutating pole converters due to the fact that the various sections of this cage winding form low-resistance closed circuits around the commutating poles. This was in accord with all evidence available to that time, and no one took exception to it. However, later experience has shown that this was incorrect, for, in later practise, it was found that the use of a complete cage damper of low resistance which decreases the hunting tendency, also greatly decreases the flashing tendency, so that today most converters of the commutating pole type are being made with complete cage dampers. Apparently, the flashing tendencies in converters due to hunting are much worse than those due to flux sluggishness. Therefore, a sacrifice can be made in one for the benefit of the other.

In the case of a dead short circuit on the d-c. side of a synchronous converter, there is liable to be flashing, just as in the d-c. machine, and the flash and the breaker opening are liable to occur so closely together that an observer cannot say which is first.

In d-c. railway motors, flashing at the commutator is not an uncommon occurrence. One rather common cause of flashing, especially at high speed, is due to jolting the brushes away from the commutator, due to rough track, etc. This is especially the case with light spring tension on the brushes. The carbon breaks contact with the copper, forming an arc which is carried around. Another prolific source of flashing is due to opening and closing the motor circuit in passing over a gap or dead section in a trolley circuit. Here the motor current is entirely interrupted, and, after a short interval, it comes on again, without any resistance in circuit except that of the motor itself. If the current rush at the first moment of closing is not too large, and if the armature and field magnetic fluxes build up at the same rate, then there is usually but small danger of a flash, except under very abnormal conditions. The rapidly changing field flux however generates heavy currents under the brushes, thus tending toward flashing. The reactance of the motor, especially of the field windings, limits the first current rush to a great extent. According to this, closed secondary circuits of low resistance around either the main poles or the commutating poles, should be objectionable, and experience bears this out.

In railway armatures, as a rule, fewer commutator bars per pole are used on the average than in stationary machines of corresponding capacity, except possibly, in large capacity motors. This is due largely to certain design limitations in such apparatus, but this has doubtless been responsible for a certain amount of flashing in such apparatus.

Average e.m.f. and "Field Form." A rather common practise has been to specify the average volts per bar in a given machine. This, in itself, does not mean anything, except in a very general way; for the limit is really fixed by the maximum volts per bar, as already shown, and there is no fixed relation between the average and the maximum volts per bar. The ratio between these two voltages is dependent upon the field flux distribution,—that is, the "field form." In practise, this ratio varies over a wide range, depending upon the preferences of the designer, upon limitations of pole space available, etc. Also, with load, it depends upon the amount of flux distortion of the field, which, in turn varies greatly in practise. In well proportioned modern machines, where space and other limitations permit, the average e.m.f. per bar is about 70 per cent of the maximum at no load, and about 55 per cent to 60 per cent with heavy load. This means that about 15 volts per bar, average, is the maximum permissible, in large machines with considerable field distortion, if a maximum of 28 volts per bar is not to be exceeded. On this basis, a 600-volt machine should therefore have not less than 40 commutator bars per pole. However, this is with considerable field distortion. If this distortion is reduced or eliminated, the average volts can be considerably higher, as in machines with high saturation in the pole faces, pole horns and armature teeth, or with compensated fields. Synchronous converters are practically self-compensated and can therefore have higher limits than the above, if the normal rated e.m.f. is never to be exceeded. However, in 600-volt converter work, in particular, wide variations sometimes momentarily occur, up to 700 to 750 volts, and such machines should have some margin for such voltage swings. The ordinary 600-volt d-c. generator also attains materially higher voltages at times, which would be taken into account in the limiting voltage per commutator bar and the total number of commutator bars per pole.

Obviously, the "fatter" the field form, the nearer the average voltage can approach the maximum. With an 80 per cent

field form, instead of 70 per cent, for instance, the number of bars per pole can be reduced directly as the polar percentage is increased; and 35 bars per pole with 80 per cent would be as good as 40 bars with 70 per cent assuming the same percentage of field distortion in both cases. An increase in the polar arc will tend toward increased distortion, but the reduced number of turns per pole should practically balance this, so that, other things being unchanged, the flux distortion should have practically the same percentage as before.

In large machines of very high speeds, large polar percentages, —that is, large "field form constants," are very advantageous, but are not always obtainable, due to the space required for the commutating pole winding. In compensated field machines, with their smaller commutating pole windings, the conditions are probably best for high field form constants, and high average volts per bar; and thus this type often lends itself very well to those classes of machines where the minimum possible number of commutator bars is necessary. This is the case with very high speeds, and also for very high voltage machines.

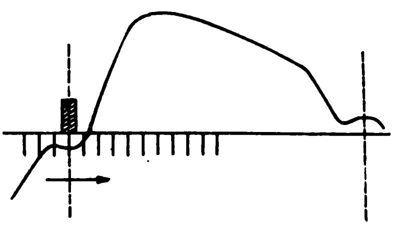

Fig. 3

Usually it is considered that the commutating conditions of a machine are practically the same with the same current, whether it be operated as a generator or motor. However, when it comes to flashing conditions, there is one very considerable difference between the two operations. In the d-c. generator, the field flux distortion by the armature is such as to crowd the highest field density, and thus the highest volts per bar, away from the forward edge of the brushes. In the motor, the opposite is the case, and therefore there is a steeply rising field, and a corresponding e.m.f. distribution in front of the brushes. As the flash is carried in the direction of rotation it may be seen that, in this particular, the generator and motor are different.

Blackening and Burning—High Mica—"Picking Up" Copper

In the preceding, certain limitations of commutation and flashing have been treated. There are, in addition, a number

of other conditions which are related closely to commutation, and which have already been touched upon to a limited extent. One of these is the permissible current density in the brushes or brush contacts.

As brought out before, there are two currents to be considered, namely, the work current which flows to or from the outside circuit, and the local or short circuit current which is purely local to the short circuited coils and the brush. The *true* current density is that due to the actual resultant current in the brush tip or face, which is very seldom uniform over the whole brush tip. The " apparent " current density is that due to the work current alone—assumed to be uniform over the brush tip. The current density very commonly has been assumed as the total work current, in and out, divided by the total brush section, and, moreover, this has been considered as the true current density, the local or short circuit currents being neglected altogether. This method of considering the matter has been very misleading, resulting in many cases, in a wrong or unsuitable size of brush being used just to meet some specified current density. In many of the old, non-commutating pole machines, the local currents were predominant under certain conditions of load, for the brushes, as a rule, had to be set at the best average position, so that at some average load, the commutating conditions would be best. At higher and lower loads, the short circuit currents were usually comparatively large. The wider the brush contact circumferentially, the greater would be the short circuit currents and the higher the actual current density at one edge of the brush, while the apparent density would be reduced. Thus, in attempting to meet a low specified current density, the true density would be greatly increased. The fallacy of this procedure was shown in many cases in which the brush contact was very greatly reduced by grinding off one edge of the brush. Very often, a reduction in circumferential width of contact to one-half resulted in less burning of the brush face. The apparent density was doubled but the actual maximum density was actually reduced. Many of these instances showed very conclusively that much higher true current densities were practicable, provided the true and apparent densities could be brought more nearly together. This is what has been accomplished to a considerable extent in the modern well designed commutating pole machine. In such machines, the current dis-

tribution at the brush face is nearly uniform under all conditions of load. It is not really uniform, even in the best machines; but the variations from uniformity, while possibly as much as 50 per cent in good machines, is yet very small compared with the variation in some of the old non-commutating pole machines. In consequence, it has been possible to increase the apparent current densities in the brushes in modern commutating pole machines very considerably above former practise, while still retaining comparatively wide brush faces. In fact, the width of the brush contact circumferentially is not particularly limited if the commutating field flux can be suitably proportioned; that is, where a suitable width and shape of commutating field can be obtained. In many of the old time machines, an apparent density of 40 amperes per square inch under normal loads was considered as amply high, while at the present time, with well proportioned commutating poles, 50 per cent higher apparent densities are not uncommon. However, experience shows that the same brushes, with perfectly uniform distribution of current at the brush face, can carry still higher currents. Therefore, in modern commutating pole machines, the actual upper limit of brush capacity is not yet attained. But there are reasons why this upper limit is not practicable. One reason is that already given, that uniform current distribution over the brush face is seldom found. This means that a certain margin must be allowed for variations. A second reason lies in the unequal division of current between the various brushes and brush arms. This may be due initially to a number of different causes. However, when a difference in current once occurs, it tends to accentuate itself, due to the negative coefficient of resistance of the carbon brushes and brush contacts. If one of the brushes, for instance, takes more than its share of current for a period long enough to heat the brush more than the others, then its resistance is lowered and it tends to take still more current. If there were no other resistance in the current path, it is presumable that the parallel operation of carbon brushes would be more or less unsatisfactory. In the practical case, however, instead of the operation being impracticable, it is merely somewhat unstable. Unequal division of current between the brushes on the same brush arms, is to some extent, dependent upon the total current per arm. Where there are many brushes in parallel and the total current to be carried is very large, it is obvious that one brush may take

an excessively large current without materially decreasing the current carried by the other brushes. As a rule, the larger the current per arm, the more difficult is the problem of properly balancing or distributing the current among all the brushes. Schemes have been proposed, and patented, for forcing equal division, but, as a rule, they have not proved very practicable, although some comparatively simple expedients have been tried out with a certain degree of success.

In the same way, the division of current among brush arms of the same polarity is not always satisfactory. 50 per cent variation of current between different arms is not very unusual, and the writer has seen a number of instances where the variation has been 100 per cent, or even much more. Obviously, with such variation, it is not practicable to work the brushes up to the maximum density possible, for some margin must be allowed for such unbalancing.

Experience has shown that when current passes through a moving contact, as from a brush to the commutator copper, or *vice versa*, a certain action take place which resembles electrolytic action to some extent, although it is not really electrolytic. It might also be said to resemble some of the actions which takes place in an arc. Minute particles appear to be eaten or burned away from one contact surface, and these are sometimes deposited mechanically upon the opposing surface. The particles appear to be carried in the direction of current flow, so that if the current is from the carbon brush to the copper, the commutator face will tend to darken somewhat, evidently from depositation of carbon. If the current is from the copper to the carbon, the brush face will sometimes tend to take a coating of copper, while the commutator face will take a clean, and sometimes raw, copper appearance. As the current is in both directions on the ordinary commutator, this action is more or less averaged, and therefore is not usually noticed. With one polarity or direction of current, the commutator face eats away, while with the other direction, the brush face is eaten away and may lose its gloss.

The above action of the current gives rise to a number of limiting conditions in direct-current practise. Experience shows that this " eating away " action occurs with all kinds of brushes, and with various materials in the commutator. It appears to be dependent, to a considerable extent, upon the losses at the contact surface. In other words, it is dependent upon both the

current and the contact drop. With reduction in contact drop, this burning action apparently is decreased, but in commutating machinery, this reduction cannot be carried very far, in most cases, on account of increase in short circuit current, which nullifies the gain in contact drop. In fact, in each individual machine, there is some critical resistance which gives least loss and least burning at the contact surfaces.

Practise has shown that this burning action is very slow at moderate current densities in carbon and graphite brushes—so slow as usually to be unnoted. However, if the actual current density in the brush face is carried too high, the burning of the brushes may become very pronounced. With the actual work current per brush usual in present practise, the burning of the brush face may usually be credited to local currents in the brushes. This is one pretty good indication of the presence of excessive local currents. It also indicates the location and direction of such currents, but is not a very exact quantitative measure of them. It is not uncommon, in examining the brushes of a generator or motor, to find a dull black area under one edge of the brush, which obviously has been burned, while the remainder of the brush face is brightly polished. In severe cases, practically as good results will be obtained if the burned area is entirely cut away by beveling the edge of the brush.

This eating away of either the brush face or the commutator, and the deposit upon the opposing face, leads to certain very harmful conditions in direct-current machinery. As stated before, if the true current density is kept sufficiently low in the contact face, the burning is negligibly small in most cases. However, where the current passes from the commutator to the brush, it is the commutator copper which eats away, while the mica between commutator bars does not eat away, but must be worn away at the same rate that the copper is burnt, if good contact is to be maintained. Let the burning of the copper gain ever so little on the wear of the mica, then trouble begins. The brush begins to "ride" on the mica edges and does not make true contact with the copper. This increases the burning action very rapidly, so that eventually the mica stands well above the copper face. This is the trouble usually known as "high mica." It is frequently credited to unequal rates of wear of copper and mica. This idea of unequal wear has been partly fostered by the fact that with relatively thick

mica, the action is greatly increased, or, with very thin commutator bars, with the usual thickness of the mica, the high mica trouble becomes more serious. In both these latter cases, it is the higher percentage of mica,—that is, the relatively poorer wearing characteristics of the mica itself, which is at fault. But the commutator copper does not *wear away.* In fact, it is not physically possible for it to *wear* below the mica. It is "eaten away" or burned, as described above. In some special cases, where this burning is unusually severe, the mica apparently wears down about as fast as the copper, so that the commutator remains fairly clean and has no particularly burnt appearance, but grooves or ridges, showing undue wear. But this rapid apparent wear is a pretty good indication that excessive burning action is present at times, usually due to excessive local currents. In some cases, this burning action may be present only during heavy or peak loads which may be so interspersed with periods of light running that the true wear of the mica catches up with the burning of the copper. In such cases, the commutator may have a beautiful glossy appearance normally, but may wear in grooves and ridges. On account of this burning action, practise has changed somewhat in regard to staggering of brushes on commutators to prevent ridging between the brushes. Formerly, it was common practise to displace all the positive brushes one direction axially, and the negatives in the other direction, in order to have the brushes overlap. This, however, did not entirely prevent ridging, for the burning of the copper occurred only under one polarity. It is now considered better practise to stagger the arms in pairs.

With commutating pole machines, the true current densities in the brushes are carried up to as high a point as the non-burning requirements will permit. Reduction in local currents has been accompanied by increase in the work current density. Therefore, conditions for burning and high mica are still existent, as in non-commutating pole machines. In recent years, a new practise, or rather an extension of an old practise, has been very generally adopted, namely, undercutting the mica between bars. In early times, such undercutting was practised to a certain extent, usually however, to overcome mica troubles principally. In the newer practise, such undercutting is primarily for other reasons, although the mica problem is partly concerned in it. During the last few years, extended experience has shown that graphite brushes, or carbon brushes with

considerable graphite in them, are extremely good for collecting current, but on the other hand, are very poor when it comes to wearing down the mica, due to their softness or lack of abrasive qualities. Due to the graphite constituent, such brushes are largely self-lubricating, and therefore, "ride" more smoothly on the commutator than the ordinary carbon brush. They are therefore much quieter, and this is a very important point with the present high speeds which are becoming very much the practise. However, by undercutting the mica, all difficulty from lack of abrasive qualities in the brush is overcome, and thus the good qualities of such brushes could be utilized. The advantage of self-lubricating brushes should be apparent to anyone who has had difficulties from chattering and vibration of brushes, due to lack of lubrication. Such chattering may put a commutator " to the bad " in a short time, and the conditions become cumulatively worse. Chattering means bad contact between the brush and commutator, which in turn, means sparking and burning, which means increased chattering or vibration.

The above refers to burning of the commutator face. But such burning also may have a bad effect on the brushes. When the commutator copper burns away to any extent, it may deposit on the brush face following the direction of the current. This coating on the brush face sometimes leads to serious trouble, by lowering the resistance of the contact surface. This not only allows larger short circuit current and greater heating of the brush, but it makes the resistance of that particular path lower than that of other parallel brush paths. In consequence, the coated brush takes an undue share of the total current, as well as an unduly large local current. The resultant heating may be such that the brush actually becomes red hot or glows. This heating further reduces the resistance, and tends to maintain the high temperatures. This glowing or overheating very frequently causes disintegration of the binding or other material in the brush, so that it gradually honeycombs at or near its tip. This action may keep up until the brush makes bad contact. It may be that a similar action may occur coincidently on other brushes, but, there is no uniformity about it. This action of transferring copper to the brush is sometimes known as " picking up copper." It is not limited to brushes of one polarity, except where the metallic coating is caused primarily by the work current. Where it results from

high local currents, it may be on the brushes of either polarity, for the local currents go in and out at each brush. However, according to the writer's experience, this coating is more common on the one polarity.

Glowing and honeycombing of brushes is not necessarily dependent upon the metallic coating on the brushes, although this latter increases the action. Anything that will unduly increase the amount of current in any brush contact for a period long enough to result in heating and lower contact resistance, with brushes in parallel, may start this glowing and honeycombing. It is not as common an action in modern machines as in old time ones.

As an evidence that poor contact or high contact drop tends to produce burning, may be cited the fact that, in many cases of apparent rapid wear of the commutators, such wear has been practically overcome by simply undercutting the mica and thus allowing more intimate contact between brush and copper. In some instances, this also lessened or eliminated the tendency to pick up copper. Thus undercutting has been very beneficial in quite a number of ways.

Number of Slots, Conductors Per Slot, Etc.

There are certain limitations in direct-current machines, depending upon the minimum number of slots per pole which can be used. Provided satisfactory commutating conditions can be obtained, it is in the direction of economy of design to use a relatively low number of slots per pole, with a correspondingly large number of coils per slot. This is effective in several ways. In the first place, insulating space is saved, thus allowing an increase in copper or iron sections, either of which allows greater output. In the second place, wider slots are favorable to commutation. Thus the natural tendency of d-c. design is toward a minimum number of slots per pole. But if this is carried too far, certain objections or disadvantages arise or become more prominent, so that at some point they overbalance the advantageous features. As the slots are widened and the number of teeth diminished, variations in the reluctance of the air gap under the main poles, with corresponding pulsations in the main field flux become more and more pronounced. These may effect commutation, as the short circuited armature coils form secondary circuits in the path of these pulsations. But before this condition becomes objec-

tionable, other troubles are liable to become prominent, such as "magnetic noises," etc. If the machine is of the commutating pole type, there are liable to be variations in the commutating pole air gap reluctance, so that it may be difficult to obtain proper conditions for commutation. A relatively wide commutating zone is required if there are many coils per slot; also, all the conductors per slot usually will not commutate under equal conditions, which may result in blackening or spotting of individual commutator bars symmetrically spaced around the commutator, corresponding to the number of slots. In non-commutating pole machines, it may be difficult to find a suitable field or magnetic fringe in which to commutate, and thus the first and last coil in each slot will have quite different fluxes in which to commutate.

Depending upon the relative weight of the various advantages and disadvantages of a small number of slots per pole, practise varies greatly in different apparatus. In small and medium capacity railway motors, where maximum output in minimum space is of first importance, and where noise, vibrations, etc. are not very objectionable, the number of slots per pole used is probably lower than in any other line of d-c. machines, six to eight per pole being rather common. In the smaller and medium size stationary motors, where noise must be avoided, a somewhat larger number of slots is used in general, depending somewhat upon the size of the machine. On still larger apparatus, excepting possibly, small low-speed engine type generators, 10 slots or more per pole are used in most cases, and, in general, more than 12 are preferred. In the large 600-volt machines, the number is fixed partly by the minimum number of commutator bars per pole, and the number of coils per slot. Assuming three coils per slot, then with a minimum number of commutator bars of about 40 per pole, the minimum number of slots per pole will be 14, and with two bars per slot, will be correspondingly larger. This therefore represents one of the limits in present practise.

Noise, Vibration, etc. Mention has been made of limitations of noise and vibration being reached, in considering the minimum number of slots. This is a very positive limitation in design, especially so in recent years, when everything is being carried as close as possible to all limits in economies in materials and constructions. All the various conditions which cause undue noises in electrical apparatus are not yet well known,

and the application of remedies is more or less a question of "cut-and-try."

A fundamental cause of noise in direct-current machines lies in very rapid pulsations or fluctuations in magnetic conditions. This has been well known for years, and many solutions of the problem of preventing such variations in magnetic conditions from setting up vibrations and consequent noise, have been proposed, but many of them appear to hold only for the particular machine, or line of machines, for which they were devised. A perfectly good remedy in one machine not infrequently proves an utter failure on the next one. There are certain remedies for noise in direct-current machines which apply pretty generally to all machines, but, as a rule, such remedies mean more expensive constructions. In general, large air gaps and gradual tapering of the flux at the pole edges tend toward quiet operation. A large number of slots per pole tends toward quietness. However, the trend of design has been toward very small air gaps, especially in recent designs of small and moderate size d-c. motors; also, the aim has been to use as few armature slots as possible. Moreover, newer designs with steel or wrought iron frames, as a rule, have the magnetic material in the frames reduced to the lowest limit that magnetic conditions will permit. Also, with the general use of commutating poles, the tendency has been toward "strong" armatures and correspondingly weak fields, so that the total field fluxes and field frames are relatively small compared with the practise of a few years ago. With these small frames, resonant conditions not infrequently are encountered, especially in those machines which are designed to operate over a very wide range in speed. There is liable to be some point in the speed range where the poles or frame, or some other part, is properly tuned to some pulsating torque or "magnetic pull" in the machine. In such case, a very slight disturbance of a periodic nature may act cumulatively to give a very considerable vibration and consequent noise.

The pulsations in magnetic conditions which produce vibration may be due to various causes, but, as a rule, the slotted armature construction is at the bottom of all of them. Open type armature slots usually are much worse than partially closed slots. Such open slots produce "tufting" or "bunching" of the magnetic flux between the field and armature, and it is this bunching of flux which usually, in one form or another,

produces a magnetic pulsation or pull which sets up vibration. This bunching of lines may be such as to set up pulsating magnetic pulls at no-load as well as full load. In other cases, the ampere turns in the armature slots tend to exaggerate or accentuate the bunching so that the vibration varies with the load. This bunching of the flux may act in various ways. The total air gap reluctance between the armature and main poles may vary or pulsate, so that the radial magnetic pull between any main pole and the armature will pulsate in value. If the reluctances under all the poles are varying alike, then these pulsating radial pulls will tend to balance each other at all instants. However, if the reluctances under the different poles do not vary simultaneously, then there are liable to be unbalanced radial magnetic pulls of high frequency, depending upon the number of armature teeth, speed of rotation, etc. If this frequency is so nearly in tune with the natural period of vibration of some part of the machine, such as the yoke, poles or pole horns, armature core and shaft, that a resonant condition is approximated, then vibration and noise are almost sure to occur.

Radial unbalanced pulls, as described, are liable to occur when the number of armature teeth is other than a multiple of the number of poles; and the smaller the number of teeth per pole, the larger will be the unbalancing in general. As a remedy, it might be suggested that the number of armature slots always be made a multiple of the number of poles. However, there are several objections to this. One serious objection is that, on small and moderate size d-c. machines, the two-circuit type of armature winding is very generally used, and, with this type of winding, the number of armature coils and commutator bars must always be one more or less in number than some multiple of the number of pairs of poles. Mathematically therefore, with a two-circuit winding, the number of slots can never be a multiple of the number of poles unless an unsymmetrical winding is used, that is, one with a " dummy " coil. A second objection to using a number of slots which is a multiple of the number of poles, is that there are pulsating magnetic pulls which may be exaggerated by this very construction. There are two kinds of magnetic pulls, a radial, which has already been considered, and a circumferential, due to the tendency of the armature core to set itself where it will enclose the maximum amount of field flux. Obviously, if the arrangement of slots is such that when

one pole has a maximum flux into the teeth, another pole has a minimum, then the circumferential puslations in torque will be less than if all poles enclosed the maximum or the minimum flux simultaneously. This latter condition will be produced when the number of armature slots is a multiple of the number of poles. Therefore, in dodging unbalanced radial magnetic pulls by using a number of armature slots which is a multiple of the number of poles, the designer is liable to exaggerate the circumferential variations in torque or pull, so that he is no better off than before. This circumferential pulsating magnetic pull may act in various ways to set up vibration, and if there is any resonant condition in the machine, vibration and noise will result.

Several years ago, the writer made some very interesting tests on a number of d-c. machines to discover the nature of the vibrations which were producing noise. These machines had very light frames and were noisy, although not excessively so. The following results were noted: In certain four-pole machines, it was noted that the frames vibrated in a radial direction, as could be easily determined by feeling. However, upon tracing around the frame circumferentially, nodal points were noted. In some cases, there were points of practically no vibration midway between the poles, as at A in Fig. 4. In other cases the point of least vibration was at B, directly over the main poles. Apparently, minimum vibration at A and maximum at B occurred when the pulsating magnetic pulls were in a radial direction, while, with circumferential pulls, the maximum vibration was at A. It was also noted in some instances that a variation in the width of the contact face of the pole against the yoke produced vibrations and noise, and nodal points in the yoke, the vibrations being a maximum at A.

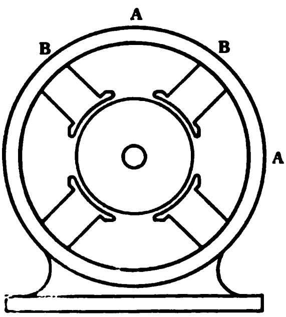

FIG. 4

In still other cases in commutating pole machines, vibrations and noise were apparently set up by either radial or circumferential magnetic pulsations under the commutating poles themselves, as indicated by the fact that removal of the commutating poles, or a considerable increase in their air gaps, tended to overcome the noise. In such cases, the noise usually increased with the load, in constant speed machines.

Skewing of the armature slots, or of the pole faces, has proven quite effective in some cases of vibration and noise. Tapered air gaps at the pole edges have also proven effective in many individual cases. However, the causes of the trouble and the remedies to be applied in specific cases are so numerous and so varied that at present it is useless to attempt to give any limitations in design as fixed by noise and vibration due to magnetic conditions.

"Flickering" of Voltage, and "Winking" of Lights

From time to time, cases have come up where noticeable "winking" of incandescent lights occur, this being either of a periodic or non-periodic character, the two actions being due to quite different causes. In either case, the primary cause of the difficulty may be in the generator itself, or it may be in the prime mover. The characteristics of the incandescent lamp itself tends, in some cases, to exaggerate this winking. To be observable when periodic, the period must be rather long, corresponding to a very low frequency. Periodic flickering of voltage may be considered as equivalent to a constant d-c. voltage with a low-frequency small-amplitude alternating e.m.f. superimposed upon it. In view of the fact that incandescent lamps of practically all kinds give satisfactory service without flicker at 40 cycles with the impressed e.m.f. varying from zero to 40 per cent above the effective value, one would think that a relatively small variation of voltage, of 3 per cent or 4 per cent for instance, would not be noticeable at frequencies of 5 to 10 cycles per second. However, careful tests have shown that commercial incandescent lamps do show pronounced flicker at much lower percentage variations in voltage, depending upon the thermal capacity of the lamp filament. Based on such thermal capacity, low candle power 110-volt lamps, for example, should show more flicker than high candle power lamps. Also, tungsten lamps for same candle power should be more sensitive than carbon lamps, due to their less massive films. In fact, trouble from winking of lights has become much more pronounced since the general introduction of the lower-candle power, higher-efficiency incandescent lamps.

In view of the fact that winking has been encountered with machines in which no pronounced pulsations in voltage appear to be possible, a series of tests was made some years ago to determine what periodic variation was noticeable on ordinary

low-candle power Tungsten and carbon lamps. A lamp circuit was connected across a source of constant direct e.m.f., and in series with this circuit was placed a small resistance which could be varied at different rates and over varying range. The results were rather surprising in the very low pulsations in voltage which showed flickering of the light when reflected from a white surface. With the ordinary frequencies corresponding to small engine type generators—that is, from 5 to 10 cycles—periodic variations in voltage of ½ per cent above or below the mean value were sufficient to produce a visible wink, with 16-candle power carbon lamps; while 1 per cent variation above and below was quite pronounced. With corresponding tungsten lamps, only about half this variation is sufficient to produce a similar wink. These tests were continued sufficiently to show that such periodic fluctuations in voltage must be limited to extremely small and unsuspected limits. This condition therefore imposes upon the designer of such apparatus a degree of refinement in his designs which is almost a limitation in some cases.

It is probable that non-periodic fluctuations in voltage do not have as pronounced an effect in regard to winking of lights as is the case with periodic fluctuations, if they do not follow each other at too frequent intervals, unless each individual pulsation is of greater amplitude, or is of longer duration. Possibly a momentary variation in voltage of several per cent will not be noted, except by the trained observer, unless such variation has an appreciable duration.

A brief discussion of the two classes of voltage variations may be of interest, and is given below.

Periodic Fluctuations. As stated before, these may be due to conditions inside the machine itself, or may be caused by speed conditions in the prime mover. Not infrequently, the two act together. Variations in prime mover speed can act in two ways; first, by varying the voltage directly in proportion to the speed, and second, by varying the voltage indirectly through the excitation, the action being more or less cumulative in some cases. Such speed variations usually set up pulsations corresponding directly to the revolutions per minute and independent of the number of poles on the machines.

In the machine itself, periodic pulsations of frequency lower than normal frequency of the machine itself, may be caused by magnetic dissymmetry of some sort, or by unsymmetrical windings. Usually, such dissymmetries give voltage fluctua-

tions at a frequency corresponding to the normal frequency of the machine, and therefore will have no visible effect unless such normal frequency is comparatively low, which is usually the case in engine type d-c. generators. In other cases, these dissymmetries may give pulsations corresponding to the revolutions, and not the poles. For instance, if the armature periphery and the field bore are both eccentric to the shaft, then magnetic conditions are presented which vary directly with the revolutions.

However, there have been cases where no dissymmetry could be found, and yet which produced enough variations to wink the lights. Usually in such cases, the number of armature slots per pole was comparatively small, and the trouble was overcome by materially increasing the number of slots per pole. A second source of winking has been encountered in some three-wire machines in which the neutral tap is not a true central point. In such case, the neutral travels in a circle around the central point and impresses upon the d-c. voltage a pulsation corresponding to the diameter of the circle. Its frequency however, is that of the machine itself and is therefore more noticeable on low frequency machines, such as engine type generators.

Non-Periodic Pulsations or Voltage "Dips." In all d-c. generators, there is a momentary drop or "dip" in voltage with sudden applications of load, the degree of drop depending upon the character and amount of load, etc. The effects of this have been noted most frequently in connection with electric elevator operation, in which the action is liable to be repeated with sufficient frequency to cause complaint. Various claims have been made that certain types of machines did not have such voltage dips, and that others were subject to it. In consequence, the writer and his associates made various tests in order to verify an analysis of this action which is given below.

The explanation of this dip in voltage is as follows. Assume, for instance, a 100-volt generator supplying a load of 100 amperes—that is, with one ohm resistance in circuit. The drop across the resistance is, of course, 100 volts. Now, assume that a resistance of one ohm is thrown in parallel across the circuit. The resultant resistance in circuit is then one-half ohm. However, at the *first instant* of closing the circuit through the second resistance, the total current in the circuit is only 100 amperes, and therefore the line voltage at the first instant momentarily must drop to 50 volts. However, the e.m.f.

generated in the machine is 100 volts, and the discrepancy of 50 volts between the generated and the line volts results in a very rapid rise in the generator current to 200 amperes. If the current rise could be instantaneous, the voltage dip would be represented diagrammatically by a line only; that is, no time element would be involved. However, *the current cannot rise instantaneously in any machine*, due to its self-induction, and therefore, the voltage dip is not of zero duration, but has a more or less time interval. The current rises according to an exponential law, which could be calculated for any given machine if all the necessary constants were known. However, such a great number of conditions enter into this that is it usually impracticable to predetermine the rate of current rise in designing a machine; and it would not change the fundamental conditions if the rate could be predetermined, as will be shown later.

A rough check on the above theory could be obtained in the following manner, by means of oscillograph tests. For example, it was assumed in the above illustration that with one ohm resistance in circuit, an equal resistance was thrown in parallel, which dropped the voltage to one-half. In practise, the actual drop which can be measured might not be as low as one-half voltage, as the first increase in current might be so rapid as to prevent the full theoretical dip from being obtained. However, an oscillograph would show a certain amount of voltage drop. If now, after the current has risen to 200 amperes and the conditions become stable, the second resistance of one ohm is thrown in parallel with the other two resistances of one ohm each, then in this latter case, the resultant resistance is reduced to two-thirds the preceding value, instead of one-half, as was the case in the former instance. Therefore, the dip would be less than in the former case. Again, if one ohm resistance is thrown in parallel with three resistances of one ohm each, the resultant resistance becomes three-fourths of the preceding value,—that is, the voltage dip is still less. Therefore, according to the above analysis, if a given load is thrown on a machine, the dips will be relatively less the higher the load the machine is carrying. Also, if the *same percentage* of load is thrown on each time, then the dips should be practically the same, regardless of the load the machine is already carrying. For example, if the machine is carrying 100 amperes, and 100 amperes additional is thrown on, the dip should be the same as

if the machine were carrying 300 amperes and 300 amperes additional were thrown on.

Also, according to the above theory, a fully compensated field machine, (that is, one with a distributed winding in the pole faces proportioned to correctly neutralize the armature magnetomotive force) should also show voltage dips with load thrown on. To determine if this is so, several series of tests were made on a carefully proportioned compensated field machine. Two series of tests were made primarily. In the first, *equal increments of currents* were thrown on, (1) at half load, (2) at full load, and (3) at $1\frac{1}{2}$ load on the armature. In the second series of tests, a *constant percentage* of load was thrown on; that is, at half load the same current was thrown on as in the first test, while at full load, twice this current, and at $1\frac{1}{2}$ load, three times this current was thrown on.

According to the above theory, all these should show voltage dips, although the machine was very completely compensated. Also, in the first series of tests, the dips should be smaller with the heavier loads on the machine, while in the second series they should be the same in all tests. This is what the tests indicated. In the first series, the dips in voltage varied, while in the second series, they were practically constant. The results of these tests are shown in the following table. (The oscillograph prints were so faint that it was not considered practicable to produce them in this paper.)

NORMAL E.M.F.—1200 VOLTS.

Test.	Load on generator.	Increase in load.	Dip in voltage. (Approx).
A	0 Amps.	417 Amps.	700 Volts.
B	208 "	80 "	300 "
C	417 "	80 "	200 "
D	625 "	80 "	150 "
E	417 "	160 "	300 "
F	625 "	240 "	300 "

Tests, B C and D in the table show the dips for the first series of tests, while B, E and F show results for second series. The time for recovery to practically normal voltage was very short in all cases, varying from 0.002 to 0.004 seconds according to the oscillograph curves, but even with this extremely

short time, there was very noticeable winking of tungsten lamps, in practically all tests. The oscillograph curves showed practically no change in field current, except in test A.

The machine used in these tests was a special one in some ways. It was a 500-kw., 1200-volt, railway generator with compensating windings and commutating poles. In order to keep the peripheral speed of the commutator within approved practise, it was necessary in the design to reduce the number of commutator bars per pole, and consequently the number of armature ampere turns, to the lowest practical limit. This resulted in an armature of very low self induction, which was very quick in building up the armature current with increase in load. This machine therefore did not show quite as severe variations as would be expected from a normal low-voltage machine of this same construction. However, these two series of tests did show pronounced voltage dips which were sufficient to *produce noticeable winking* of incandescent lamps. Presumably, therefore, all normal types of generators will wink the lights under similar conditions.

Data obtained on non-compensated machines of 125 and 250 volts indicate the same character of voltage dips as were found in the above tests. This should be the case, for, by the foregoing explanation, the compensating winding has no direct relation to the cause of the dip.

It will be noted in these curves that the voltage recovers to normal value very quickly. However, incandescent lamps will wink, even with this quick recovery, if the dip is great enough. There is some critical condition of voltage dip in each machine which would produce visible winking of lights. Any increments of load up to this critical point will apparently allow satisfactory operation. If larger loads are to be thrown on, then these should be made up of smaller increments, each below the critical value, which may follow each other in fairly rapid succession. In other words, the rate of application of the load is of great importance, if winking of lights is to be avoided. Therefore, the type of control for motor loads, for instance, should be given careful consideration in those cases where steadiness of the light is of first importance, and where motors and lights are on the same circuit.

An extended series of tests has shown that, in most cases, 10 per cent to 15 per cent of the rated capacity of the generator can be thrown on in a single step without materially affecting

the lighting on the same circuit, and provided the prime mover holds sufficiently constant speed. However, judging from the quickness of the voltage recovery, the prime mover, if equipped with any reasonable flywheel capacity, cannot drop off materially during the period of the voltage dip as shown in the curves. The dip in voltage due to the flywheel is thus apparently something distinct from the voltage dip due to the load. However, if the load is thrown on in successive increments at a very rapid rate, the result will be a dip in voltage due to the prime mover regulation, although the voltage dips due to the load itself may not be noticeable.

The above gives a rough outline of this interesting but little understood subject of voltage variations. Going a step farther, a similar explanation could be given for voltage rises when the load is suddenly interrupted, in whole or in part. This is usually known as the inductive kick of the armature when the circuit is opened. This may give rise to momentarily increased voltages which tend to produce flashing, as has already been referred to under the subject of flashing when the circuit breaker is opened.

Peripheral Speed of Commutator

This presents two separate limitations in d-c. design, one being largely mechanical and the other being related to voltage conditions. As regards operation, the higher the commutator speed, as a rule, the more difficult it is to maintain good contact between brushes and commutator face. This is not merely a function of speed, but rather of commutator diameter and speed together. Apparently it is easier to maintain good brush contact at 5000 ft. per minute with a commutator 50 in. in diameter than with one of 10 in. in diameter. Very slight unevenness of the commutator surface will make the brushes "jump" at high peripheral speeds, and the larger the diameter of the commutator with a given peripheral speed, the less this is.

The peripheral speed of the commutators is also limited by constructive conditions. With the usual V-supported commutators, the longer the commutator, the more difficult it is to keep true, especially at very high speeds and the higher temperatures which are liable to accompany such speeds. Therefore, the allowable peripheral speeds are, to some extent, dependent upon the current capacity per brush arm, for the length of the commutator is dependent upon this. The per-

missible speed limits, as fixed by mechanical constructions, have been rising gradually as such constructions are improved. At the present time, peripheral speeds of about 4500 ft. per minute are not uncommon with commutators carrying 800 to 1000 amperes per brush arm. In the case of 60-cycle, 600-volt synchronous converters, 5200- to 5500-ft. speeds are usual with currents sometimes as high as 500 to 600 amperes per arm. In the case of certain special 750-volt, 60-cycle converters, operated two in series, commutator speeds of about 6400 ft. have proved satisfactory. These latter, however, had comparatively short commutators.

For the small diameter commutators used in d-c. turbo-generator work, peripheral speeds of 5500 to 6000 ft. have been common. However, such machines usually have very long commutators and of the so-called "shrink-ring" construction. The brushes may not maintain good contact with the commutator at all times, and in a number of machines in actual service, the writer, in looking at the brush operation, could distinctly see objects beyond the brush contacts; that is, one could see "through" the contact, and curiously, in some of these cases, the machines seemed to have operated fairly well. One explanation of this is that the gaps between brushes and commutator were intermittent, and, with one or more brush arms in parallel, one arm would be making good contact, while another showed a gap between brushes and commutator. Apparently, the commutators were not rough or irregular, but were simply eccentric when running at full speed and the brushes could not rise and fall rapidly enough to follow the commutator face all the time. Incidentally, it may be mentioned at this point, that with the higher commutator speeds now in use, there has come the practise of "truing" commutators *at full speed*. This is one of the improvements which has allowed higher commutator speeds.

The other limitation fixed by peripheral speed, namely, that of the voltage, is a more or less indirect one. It is dependent upon the number of commutator bars that are practicable between two adjacent neutral points; or, in other words, it is dependent upon the distance between neutral points. The product of the distance between adjacent neutral points and the frequency, in alternations, gives the peripheral speed of the commutator, (distance between neutral points in feet times alternations per minute equals peripheral speed in feet per

minute). With a given number of poles and revolutions per minute, the alternations are fixed. Then, with an assumed limiting speed of commutator, the distance between neutral points is thus fixed. This then limits the maximum number of commutator bars, and therefore the maximum voltage which is possible, assuming a safe limiting voltage per bar. From this it may be seen that the higher the peripheral speed, the higher the permissible voltage with a given frequency. In the same way, if the frequency can be lowered (either the speed or the number of poles be reduced) the permissible voltage can be increased with a given peripheral speed. Where the speed and the number of poles are definitely fixed and the diameter of commutator is limited by peripheral speed and other conditions, the maximum practicable d-c. voltage is thus very definitely fixed. This is a point which apparently has been misunderstood frequently. It explains why, in railway motors, for high voltages, it is usual practise to connect two armatures permanently in series; also, why two 60-cycle synchronous converters are connected in series for 1200- or 1500-volt service. In synchronous converter work, the frequency being fixed once for all, the maximum d-c. voltage is directly dependent upon the peripheral speed of the commutator.

Conclusion

The principal intent, in this paper has been to show that certain limitations encountered in d-c. practise are just what should be expected from the known properties of materials and electric circuits. The writer has endeavored to explain, in a simple, non-mathematical manner, how some of the apparently complicated actions which take place in commutating machinery are really very similar to better understood actions found in various other apparatus. An endeavor has also been made to show that a number of the present limitations in direct current design and operation are not based merely upon lack of experience, but are really dependent upon pretty definite conditions, such as the characteristics of carbon brushes and brush contacts, etc. Possibly a better understanding of the characteristics and functions of carbon brushes will result from this paper.

The writer makes no claims to priority for many of the ideas and suggestions brought out in this paper. However, much of the material is a direct result of his own investigations and those of his associates during many years of experience with direct-current apparatus.

APPENDIX

The following method of determining the maximum capacity which can be obtained with given dimensions and for assumed limitations as fixed by commutation, flashing and other conditions, is based upon certain formulas which the writer developed several years ago, and which appeared in a paper before the Institute.*

On page 2389 of the 1911 TRANSACTIONS of the Institute, the following general equation is given:

$$E_c = \frac{I_c\, W_t\, R_s\, T_c\, \pi}{10^8}\left[c_1\,(L - L_1)\,\frac{2\,Dp}{(0.25\,p + 0.5)\;(D + P_p)}\right.$$

$$\left. + c_2\,\frac{4\,D}{p}\,(0.9 + 0.035\,N) + c_3\,\frac{L}{s}\,(1.33\,d_s + 0.52 + 2.16\,s\,\sqrt{n})\right]$$

$$+\frac{c_4 2\phi\; Np\, R_s T_e}{10^8} \qquad (1)$$

Where I_c = Current per armature conductor.
W_t = Total number of armature conductors.
T_c = Turns per armature coil or commutator bar.
L & L_1 = Width of armature core and commutating pole faces respectively.
D = Diameter of armature.
p = No. of poles.
N = No. of slots per pole.
d_s = Depth of armature slot.
s = Width of armature slot.
n = Ratio of width of armature tooth to slot at surface of core.
c_1, c_2, c_3, c_4 are design constants.

In order to simplify the above equation, the following assumptions are made:

(a) No bands are used on armature core, thus eliminating the last term in the above equation.

(b) $L_1 = L$, thus eliminating the first expression inside the bracket in the above equation.

Both the above assumptions are in the direction of increased capacity with a given short circuit voltage, E_c.

Equation (1) then becomes,

**A Theory of Commutation and Its Application to Interpole Machines*, A. I. E. E., TRANS. 1911.

$$E_c = \frac{I_c W_t R_s T_c \pi}{10^8}\left[c_2 \frac{4\ D}{p}(0.9 + 0.035N)\right.$$

$$\left. + c_3 \frac{L}{s}(1.33d_s + 0.52 + 2.16\ s\ \sqrt{n})\right] \qquad \textbf{(2)}$$

The various terms in equation (**2**) should be put in such form that limiting values can be assigned to them as far as possible. In order to do this the equation can be condensed and simplified as follows, for large machines:

(a) Assuming parallel type windings,—

$W_t = \frac{T_c 2p\ E}{V_b}$, where V_b = Average volts per commutator bar or coil.

$I_c = \frac{I_t}{p}$, where I_t = Total current.

IE = Kilowatts $\times 10^3 = Kw\ 10^3$

Also, $R_s\ p = 2f$, where f = Frequency in cycles per second.

Therefore, $\frac{I_c W_t R_s T_c \pi}{10^8} = \frac{Kw_p \times 4 f T_c^2 \pi}{V_b \times 10^5}$, Kw_p being the kilowatts per pole.

(*b*) Let P_t = Armature tooth pitch.

$$\text{Then } D = \frac{Np\ P_t}{\pi}$$

$$\text{and } c_2 \frac{4\ D}{p}(0.9 + 0.035\ N) = c_2 \frac{4N}{\pi}(0.9 + .035\ N)\ P_t$$

In case of a chorded winding, the term 0.035 N should be 0.035 N_1, where N_1 represents the number of teeth or tooth pitches spanned by the coil.

(c) In the second term inside the bracket in equation (**2**), the ratio $\frac{L}{S}$ can be transformed into an expression containing P_t, as follows:

$$E = \frac{B_t\ S_t\ C_p\ R_s\ W_s}{10^8}$$

B_t = Flux density in armature teeth.
S_t = Section of iron in armature teeth.
C_p = Field form constant (percentage polar area).
R_s = Revolutions per second.
W_s = Wires in series.
S_t = $N\,T\,p\,L\,c_5$, where T = Width of tooth, and c_5 = the ratio of actual iron to the core width L.

As an approximation, $T_{xs} = \frac{P_t^2}{4}$. (This is a fairly close approximation within practical limits in the usual armature constructions).

$$\text{Then, } S_t = N\,p\,c_5\,\frac{P_t^2}{4}\left(\frac{L}{s}\right)$$

$$\text{and } E = \frac{B_t\,C_p\,R_s\,W_s\,N\,p\,c_5\,P_t^2}{4 \times 10^8}\left(\frac{L}{s}\right)$$

$$\text{or} \qquad \frac{L}{S} = \frac{4 \times 10^8\,E}{B_t\,C_p\,R_s\,W_s\,N\,p\,c_5\,P_t^2}$$

This can further be condensed as follows:

$$W_s = T_c\,\frac{2E}{V_b}, \text{ and } R_s\,p = 2\,f$$

$$\text{Therefore, } \frac{L}{s} = \frac{10^8\,V_b}{B_t\,C_p\,N\,f\,c_5\,P_t^2 T_c}$$

(d) The expression $(1.33\ d_s + 0.52 + 2.16\,s\sqrt{n})$ can be modified as follows,

$$\sqrt{n} = \sqrt{\frac{T}{s}} = \sqrt{\frac{P_t^2}{4s^2}} = \frac{P_t}{2s} \text{ on the basis that } T_{xs} = \frac{P_t^2}{4}$$

approx.

Then, $2.16\ s\sqrt{n} = 1.08\ P_t$ approx.

and, $(1.33\ d_s + 0.52 + 2.16\ s\sqrt{n}) = (1.33\ d_s + 0.52 + 1.08\ P_t)$

Substituting all the above transformations in equation (**2**) we get,

$$E_c = \frac{K w_p\,f\,T_c^2\,4}{V_b \times 10^5}\Bigg[c_2 4\ (0.9 + 0.035\ N_1)\ N\,P_t$$

$$+ \frac{\pi\,c_3\,V_b\,10^8}{B_t\,C_p\,N\,f\,c_5\,P_t^2\,T_c}\ (1.33 d_s + 0.52 + 1.08\ P_t)\Bigg] \qquad \textbf{(3)}$$

$$Kw_p = \frac{E_c\, V_b\, 10^5}{4\, T_c^2}$$

$$\frac{P_t^2}{\left[4c_2\,(0.9 + 0.035N_1)\,NfP_t^3 + \dfrac{\pi\, c_3 V_b\, 10^8}{B_t C_p N\, c_5 T_c}\,(1.33d_s + 0.52 + 1.08\, P_t\right]} \quad (4)$$

Maximum Kilowatts per Pole. Differentiating (**4**) to obtain P_t for maximum Kw_p,

$$P_t^3\, 4\, c_2\, N\, f\,(0.9 + 0.035\, N_1) = \frac{\pi\, 2\, c_3\, V_b\, 10^8}{T_c\, B_t\, C_p\, N\, c_5}\,(1.33\, d_s + 0.52)$$

$$+ \frac{\pi\, c_3\, V_b\, 10^8}{T_c B_t\, C_p\, N\, c_5} \times 1.08\, P_t \qquad (5)$$

If P_t in equation (**5**) could be derived and then substituted in equation (**4**), then for any assumed value of E_c and with the other terms given limiting values, an expression for the maximum kilowatts per pole could be obtained. The writer has not been able to solve this directly in any sufficiently simple manner, although a complicated approximate expression can be obtained. However, for practical purposes, the solution for any given conditions can be obtained by trial methods and the results plotted in curves.

For instance, in equations (**4**) and (**5**), the following terms may be given limiting values for a given class of machines and for a specified voltage.

T_c = Turns per coil.
c_2 = End flux constant.
N = Number of slots per pole. N_1 = No. of teeth spanned by coil.
c_3 = Brush short circuit constant.
V_b = Average volts per bar.
C_p = Field form constant. With max. volts per bar fixed, then V max. $\times\, C_p = V_b$.
B_t = Flux density in teeth.
c_5 = Ratio of actual iron width to core width L.

Also, type of armature winding can be fixed and departure from full pitch winding, or amount of chording can be given.

There will then remain for any assumed value of E_c, the terms,

Kw_p = Kilowatts per pole.
P_t = Tooth pitch.
f = Cycles per second.
d_s = Depth of armature slot.

All four of these latter terms are in equation (**4**), and the last three in equation (**5**). Therefore, assuming the depth of slot, equation (**5**), the values of P_t for different frequencies may be determined by trial methods. The corresponding values of P_t, f and d_s can then be substituted in equation (**4**), and the kilowatts per pole thus determined. Tables or curves can then be prepared giving the kilowatts per pole for different frequencies and for different assumed slot depths.

A series of such tables have been worked out for a specified set of conditions as given below. The assumed limiting conditions were as follows:

E_c = 4.5,—that is, one turn per coil parallel type winding is assumed.

e.m.f. = 600 volts.

C_p = 0.68

V_b = 14.3. No of commutator bars per pole = 42. No compensating winding is used. Therefore, V_b $= \frac{600}{42}$, and max. volts per bar at no load = $\frac{14.3}{0.68} = 21$. Allowing 25 per cent increase for flux distortion, and increased voltages at times, gives 26.3 at full load.

c_2 = 1.25 for average constructions.

c_3 = Varies with the number of coils per slot and the average number of bars covered by the brush, but assuming 2 bars covered, then $C_3 = 0.4$ approx. with 1 slot chording, and with either 2 or 3 coils per slot.

B_t = 150,000 lines per sq. in. on the basis of actual iron and all flux confined to the iron.

c_5 = 0.75. This allows for 90 per cent solid iron and $\frac{1}{6}$ of the total width taken up by air ducts (about $\frac{3}{8}''$ duct for each $2''$ of laminations).

$$\left.\begin{array}{ll} N & = 14 \\ N & = 21 \end{array}\right\}$$ Two cases have been assumed, one with 3 coils per slot and 14 slots per pole, and the other with 2 coils per slot and 21 slots per pole.

14 *Slios per Pole.*—Substituting the above values in equations (**4**) and (**5**), then for 14 slots per pole equation (**4**) becomes,

$$K w_p = 3767\, E_c \left[\frac{P_t^2}{f\, P_t^3 + 9.18\ (2.5\, d_s + 1) + 19\, P_t} \right] \qquad (6)$$

and equation (**5**) becomes

$$f\, P_t^3 = 18.36\ (2.5\, d_s + 1) + 19\, P_t \qquad (7)$$

Incidentally, equation (**6**) can be simplified to a certain extent by partially combining with equation (**7**), giving the following equation:

$$K w_p = 99\, E_c \left[\frac{P_t^2}{0.725\ (2.5\, d_s + 1) + P_t} \right] \qquad (8)$$

Equation (**8**), of course, can only be used with the values of P_t determined from equation (**7**).

Three values for d_s were chosen, 1 in., 1.5 in., and 2 in., which cover the practical range of design for large d.-c. generators. Frequencies from 5 to 60 cycles were also chosen. The corresponding values for P_t and Kw_p are tabulated below.

TABLE I.

f— Cycles per sec.	d_s = 1"		d_s = 1.5"		d_s = 2"	
	P_t	Kw_p	P_t	Kw_p	P_t	Kw_p
5	2.85 in.	670	3.08 in.	647	3.255 in.	620
10	2.20	453	2.362	428	2.504	407
20	1.685	299	1.828	282	1.945	266
30	1.455	235	1.575	219	1.680	208
40	1.302	197	1.417	183.5	1.515	173
50	1.20	173.5	1.305	160	1.398	151.5
60	1.125	153	1.226	143.5	1.310	135

21 *Slots Per Pole.* Substituting the proper values in equations (**4**) and (**5**) for 21 slots per pole, and one slot chording, and then solving for P_t and Kw_p for the same slot depths and frequencies, the following table is obtained:

TABLE II.

f— Cycles per sec.	d_s = 1 in.		d_s = 1.5 in.		d_s = 2 in.	
	P_t	Kw_p	P_t	Kw_p	P_t	Kw_p
5	1.985 in.	576	2.14 in.	542	2.27 in.	515
10	1.53	380	1.56	355	1.77	338
20	1.185	249	1.29	232	1.36	214
30	1.022	195	1.12	181	1.192	168
40	0.922	163	1.005	150	1.077	141
50	0.850	142	0.932	131	0.997	123
60	0.796	126	0.874	117	0.936	110

Synchronous Converters

Two cases only need be considered, namely 25 and 60 cycles. For these two cases, more definite limits can be given than for the above rather general solution for d-c. machines.

25 *Cycles.* Let N = 21, and N_1 = 20; also, assume two coils per slot for 600 volt machines.

$c_2 = 1.0.$

$c_3 = 0.37$

$B_t = 165{,}000$

$C_p = 0.7$

Then for assumed values for depth of slot of 1 in., 1.5 in., and 2 in., and for $E_c = 4.5$, the following values of P_t and Kw_p are obtained:

TABLE III.

Depth of slot.	Tooth pitch.	Kilowatts per pole.
1 in.	1.09	278
1.5	1.19	257
2	1.275	243

60 *Cycles.* Let N = 15, and N_1 = 14. Also, assume 3 coils per slot for 600 volts.

$c_2 = 1.0$

$c_3 = 0.4$

$B_t = 150.000$

$C_p = 0.66$

Then assuming slot depth of 1 in., 1.25 in., and 1.5 in., and $E_c = 4.0$, the following values of P_t and Kw_p result:

TABLE IV.

Depth of slot.	Tooth pitch.	Kilowatts per pole.
1 in.	1.14	143
1.25	1.195	137.5
1.5	1.24	132

The above tabulated results agree pretty well with practical results obtained in large generators and converters. There are so many possible variations in the limits assumed that only general results can be shown. For instance, in Table I, a constant limiting induction in the armature teeth of 150,000 lines per sq. in. is assumed. With low frequencies this can be increased, while with frequencies of 50 to 60 cycles, somewhat lower inductions will be used. Also, the commutation constant C_3 which is dependent upon the number of bars covered by the brush is naturally subject to considerable variation.

The results obtained are predicated upon parallel types of windings and a minimum of one turn per armature coil. If types of windings having the equivalent of a fractional number of turns per coil less than one, prove to be thoroughly satisfactory for large capacity machines, then the above maximum capacities can be materially increased. However, accepting the results as they stand, the limits of capacity as fixed by commutation are in general about as high as other limitations will allow.

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THE MODERN ELECTRIC MINE LOCOMOTIVE

BY GRAHAM BRIGHT

ABSTRACT OF PAPER

The day of the small mine with small equipment is passing, and in the future most of the bituminous coal mining will be accomplished in larger mines using heavy equipment. The demand for larger capacity in equipment has been increasing rapidly of late, and owing to the restricted space available for the equipment on a mine locomotive, difficulty is being experienced in designing equipment to meet the conditions. A possible solution of the problem is in providing forced ventilation for the motors which are of a type that require very little ventilation to produce a large increase in the continuous rating. This scheme has been tried out on a large locomotive and the results indicate that forced ventilation will play a prominent part in meeting the extreme severe conditions that are frequently arising in the mine locomotive field.

THIS paper will deal with a particular phase toward which some of the new mine locomotives are tending.

Motors for mine locomotives are rated in the same manner as the railway motor, that is, the one hour rating with a rise of 75 deg. cent. This rating unfortunately does not determine the fitness of the motor to meet a certain set of conditions in mine service. The mine motor is essentially an entirely enclosed motor so that the losses must be dissipated by conduction through the casing. In a locomotive with a box type frame, the air about the motor is trapped in, so that very little ventilation is obtained. With the open bar type frame the conditions are not so bad, as considerable ventilation is obtained around the motor.

The continuous rating of a mine motor is generally given at a reduced voltage since the average voltage applied to the motor in service is considerably below normal. This rating will be found to range from 35 per cent to 50 per cent of the hour rating of the motor depending upon the capacity, speed and design. It is a much simpler proposition to design a motor to give a high one hour rating than it is a high continuous rating. The hour rating depends largely upon the amount of material in the

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motor and consequently its thermal capacity. The continuous rating, however, depends upon the distribution of the material, the distribution of the losses and the ventilation. The majority of mine operators buy motors on the one hour rating, while the real capacity of a locomotive for all day service depends upon the continuous rating of its motors. For a given set of conditions the root-mean-squared current can be readily determined from a characteristic motor curve and this root-mean-squared current should not exceed the continuous capacity of the motor if the motor is not to be overloaded.

A number of operators and some engineers advocate a rating of so many horse power per ton weight of locomotive. This method may meet a great many conditions, but at times fails utterly. Unless the speed is high, a high horse power per ton cannot be utilized owing to the limited adhesion of the wheels.

The limiting dimensions, weight, gage, and rail, greatly handicap the design of a mine locomotive, and in the last few years the operating conditions have become difficult to meet owing to the increase in length of haul, weight of cars, and number of cars to be handled per trip. Some manufacturers have endeavored to meet these conditions by increasing the one hour rating of the motor while manifestly the proper thing to do is to increase the continuous rating.

About a year ago the author had occasion to estimate on a 24-ton locomotive to meet some very severe conditions. The haul was long and the grade against the loads. One manufacturer had three 85-h.p. motors as the maximum available for the equipment. According to calculations this equipment was not large enough although on a horse power per ton basis it seemed amply large (a little over 10 h.p. per ton). A second manufacturer offered a 25-ton locomotive equipped with three 115-h.p. motors.

The customer decided to try out both kinds and two locomotives of each make were installed.

The following tests made some time after the locomotives were installed clearly indicate that the high one hour rating of 115 h.p. was obtained at the expense of the continuous rating so that the 85 h.p. motor is really the larger of the two.

Both locomotives were operated in all day service and a complete record kept of the cars handled, the grades, the distances and the weights. This service was, however, much lighter than was originally specified. Table I shows the results of the

test made with the locomotive equipped with three 85-h.p. motors.

The temperatures given are actual temperatures, so that the rise indicates that the equipment is working right up to the limit and any further load added would shorten the life of the motors so that satisfactory service could not be obtained. The actual number of cars handled was about 75 per cent of the number originally specified.

Table II shows the results with the 25-ton locomotive using three 115-h.p. motors. It will be noted from this table that the work done by the 24 ton locomotive was 42 per cent greater than the 25 ton locomotive equipped with the larger motors.

TABLE I—24-TON LOCOMOTIVE

Equipment, three 85-h.p. 500-volt motors

Distance	Grade	Pull in lbs. per car.	Work done in lb-ft.
700	0	47.5	33,300
1400	2.5	142.5	200,000
1800	1.0	85.5	153,000
1600	0.425	63.5	101,100
2400	2.5	142.5	342,000
1450	1.1	89.5	130,000
1750	2.5	142.5	249,000
1880	1.06	88.0	165,500
600	3.3	173.0	104,000
		Total.	1,477,900
		Total pound miles per car. . . .	279
		Total pound miles for 725 cars	202,300

AIR TEMPERATURE 20 DEG. CENT.

	Armature	Commutator
No. 1 motor	95 deg.	97 deg.
No. 3 motor	92 deg.	97 deg.

The temperature of the motors on the 25-ton locomotive will average but two degrees lower than that of the motors on the 24-ton locomotive, showing that although the latter was doing 42 per cent more work, the temperature of its motor was practically the same as on the 25-ton locomotive, whose motors are supposed to have 37 per cent greater capacity. No doubt some of the increase in actual capacity of the 85-h.p. over the 115-h.p. motor is due to the fact that the 24-ton locomotive is equipped with the open steel bar frame which allows considerable ventilation around the motor frames, while the 25-ton locomotive is equipped with a slab steel frame which pockets the air and permits of very little ventilation. The temperature of one

motor of a second 24-ton locomotive, operating at the same time and doing about 10 per cent more work than the first, was found to have practically the same rise.

As before stated, the service conditions are becoming more severe each year until conditions are sometimes submitted that cannot be met with by any of the standard equipments from a heating standpoint. The author has had in mind for the last few years that the time is coming when forced ventilation would be necessary to meet such cases. Forced ventilation has been used very successfully for the last nine or ten years on large main line locomotives. As this particular in-

TABLE II—25-TON LOCOMOTIVE

Equipment, three 115-h.p. 550-volt motors

Distance	Grade	Pull in lb. per car.	Work done in lb-ft.
700	0	47.5	33,300
1400	2.5	142.5	200,000
1800	1.0	85.5	153,000
1600	0.425	63.5	101,000
2400	2.5	142.5	342,000
600	1.1	89.5	54,000
		Total	883,300
		Total pound miles per car	167
		Total pound miles for 851 cars	142,000

AIR TEMPERATURE 20 DEG. CENT.

	Armature	Commutator
No. 1 motor	92 deg.	95 deg.
No. 3 motor	92 deg.	95 deg.

Rating of 25-ton locomotive.............................. 345 h.p.
Rating of 24-ton locomotive.............................. 252 h.p.
Work done by 25-ton locomotive.......................... 142,000 pound-miles
Work done by 24-ton locomotive.......................... 202,300 pound-miles

stallation seemed to be such a case, permission was requested of the operating company to allow the manufacturer to install a small fan at one end of the locomotives to blow air through a duct to be so mounted that air could be delivered to the rear end of each motor. The commutator lid was raised around the edges a small amount to permit the air to escape. From 200 to 300 cu.ft. of air per minute was supplied to each motor. The motor driving the fan required about one h.p.

Before installing the fan in the locomotive a test was made on a single motor mounted on the test floor at the factory. The result of the test showed that with about 300 cu. ft. of

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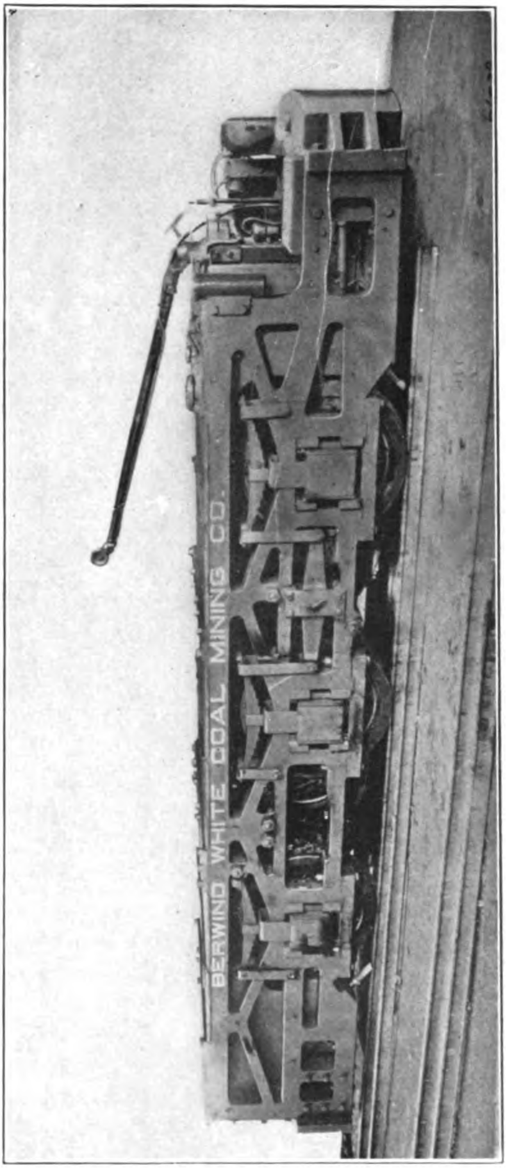

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Fig. 1—Mine Locomotive with Forced Ventilation

air per minute passing through the motor the continuous rating could be nearly doubled. Since the continuous rating of a large slow-speed motor of this type without ventilation is only about 40 per cent of the one hour rating it will be seen that with ventilation this continuous rating is still considerably below the one hour rating.

Owing to the dusty condition of the mine it was thought that trouble would be experienced by the motors being filled with dirt. During the heavy pull when bringing the trip out a great deal of dust is raised and the operators decided to run the fan only while the locomotive was going in with the empty trip.

The results have been surprising both in regard to temperature rise and the condition of the motors.

Table III shows the result of a test made by the operating

TABLE III

	Three 85-h.p. motors	Three 115-h.p. motors
Mine air at beginning of test	25 deg. cent.	25 deg. cent.
Motor frame	35 "	35 "
Motor armature	42 "	42 "
Mine air at end of day	25 "	25 "
Motor frame at end of day	75 "	93 "
Motor armature at end of day	97 "	121 "

company on the locomotive with blower, and a locomotive equipped with 115-h.p. motors without a blower. The load conditions were much more severe than on the original test and the latter locomotive was doing about 5 per cent more work than the former.

The results shown in Table III were obtained with the fan on the 24-ton locomotive operating condiserably less than 50 per cent of the time. An inspection of the inside of the motors showed that they were much cleaner than the ones not using forced ventilation. The results of the tests show conclusively that the increased capacities that are being demanded can be economically met by the use of forced ventilation with standard motors if these motors are properly designed. This will prove quite a saving to the operators, since without forced ventilation new and expensive motors would have to be be signed.

It is the intention now to install a blowing equipment on the other 24-ton locomotive and on both locomotives equipped with 115-h.p. motors. It is not probable that the 115-h.p. motor will receive as much benefit from forced ventilation as the 85-h.p. motor, due to the fact that the armature of the 85-h.p. motor is furnished with ventilating slots while the 115-h.p. motor is not.

Fig. 1 is an illustration of the 24-ton locomotive, and with its ventilating equipment it has a greater capacity than any other mine locomotive yet built.

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ABNORMAL VOLTAGES IN TRANSFORMERS

BY J. MURRAY WEED

ABSTRACT OF PAPER

This paper deals with the electrical behavior of transformer windings when subjected to steep wave fronts and high-frequency wave trains. The dependance of the internal voltages produced, upon the distribution of capacity with the inductance of the winding is discussed.

Practical windings are divided into two general classes, one in which inductance and capacity are practically uniformly distributed, and the other in which the capacity is more or less concentrated at certain points, with relatively concentrated portions of inductance intervening.

Neglecting the effects of the high frequency dielectric losses in the insulation at high frequency, distinct mathematical analysis is given to these two classes of winding to determine the ratios of the internal voltages to the voltage of the external wave or wave train. The resulting internal voltage distributions are plotted for various frequencies, and curves are plotted for the relations of maximum internal voltages to frequency. These curves show that some frequencies are dangerous, while others are not, but it can not be said that one of these types of winding is better than the other from the standpoint of the possibility of excessive internal voltages.

The analysis is by no means complete, but an examination is made of the facts and fundamental principles involved which will enable us to insulate for and guard against excessive internal voltages in a more scientific manner.

FROM THE first use of transformers, the occurrence of excessive voltages between adjacent turns or sections of the same winding, as a result of switching, sparking discharges or lightning, forced itself upon our attention by its results in punctured insulation. In the early stages of development, the effort was only to insulate adjacent turns and coils from each other in a manner to give a satisfactory factor of safety for the calculated transformer voltages, and lightning arresters were developed for protection from excessive external voltages. It was found, however, that breaks between turns—usually the end turns of the winding—were altogether too frequent. It was then recognized that a sudden application of voltage, or sudden change of voltage, at the transformer terminals, would not instantly distribute itself throughout the winding, but was

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more or less concentrated at the first instant across the end turns. It was seen that this condition was not remedied by lightning arresters, and the use of extra end turn insulation came into vogue. Also the practise of connecting choke coils between the transformer winding and the line.

Some very lively discussions occurred as to the relative merits of external inductance and end-turn insulation. Recommendations were made as to the amount of inductance necessary, on the one hand, and, on the other, for the portion of the winding requiring extra insulation. But with increased experience it was found that the protection afforded by an external inductance in many cases did not eliminate the necessity for extra turn insulation. Also that with extra end turn insulation more frequent breaks occurred further in from the ends, and, in fact, the extra insulation on the end turns was itself occasionally subject to failure. To meet the requirements for safety, as indicated by experience, this insulation has been gradually increased, and gradually extended further from the ends, until at present many large high voltage transformers have what might be called re-enforced turn insulation throughout. Where a factor of four, for instance, applied to normal voltages to ground, gives ample strength for the major insulation between the high-voltage winding and the low-voltage winding and core, a factor of from 50 to 100 times as great is used in these transformers with respect to the insulation between turns. Thus, this insulation has a strength several hundred times as great as the normal ratio voltage between turns.

In this matter of internal insulation, experience has been a tedious and a costly teacher. When failure has occurred, the cause was often so uncertain as to leave doubts as to the merits of the case. There were so many causes to which the difficulty might be ascribed, such as dirt, moisture and faulty construction or abnormal operation, that a number of failures were required to convince the designers that more insulation was needed, or that the design should be modified. Moreover it has been necessary throughout for the designer to entertain considerations not only of safety, but also of economy. Up to the present, however, he has been handicapped in his efforts to properly adjust these contending considerations by the lack of adequate physical conceptions; first, of the nature and extent of the disturbances from which external protection cannot reasonably be expected; and second, of the electrical be-

havior of the windings themselves when subjected to these disturbances. These questions have been the subject of special investigation, with the result that a new epoch in transformer design has been initiated, based upon a better knowledge of the physics involved. The present paper deals only with the second question, no consideration being given to the severity of the disturbances which may occur in practise.

Our consideration of the nature of the effects produced will be based upon two classes of disturbances, which are typical; namely, the high-frequency wave train and the abrupt wave front. If we consider the effects of sheer wave fronts, or voltage changes of given amplitude which are absolutely sudden, and of wave trains which are sustained with uniform amplitude, we will have considered conditions which are worse in these respects than the worst which occur in practise. These considerations will, however, show us the nature of the results which may occur in practise, and mathematical discussion is more easily based upon these extreme conditions.

Transformer windings are ordinarily thought of merely as large inductances. In reality, they contain a rather large amount of capacity distributed in different ways depending upon the type and arrangement of the winding. For ordinary normal operating frequencies, in a steady state, the effect of capacity is negligible, and the winding acts like a simple concentrated inductance, with voltage uniformly distributed. At high frequencies, however, or when a sudden voltage is impressed, the effect of capacity in disturbing this voltage distribution becomes important. This is due to the fact that at high frequencies, conditions of resonance are reached for the various combinations of inductance and capacity. This action will be understood when we consider certain typical combinations.

Considering first the effect of an alternating voltage impressed upon an inductance and a capacity in parallel; the current taken by the capacity, with constant voltage, is directly proportional to the frequency, while the current taken by the inductance is inversely proportional thereto. The frequency at which these currents are equal is called the resonant frequency for this combination. The direction of these currents with respect to the external circuit, or source of impressed voltage, are opposed to each other, so that this combination takes no resultant current from the external circuit at its resonant frequency, however high the voltage may be. It therefore acts, under these conditions, like an open circuit.

At frequencies below the resonant frequency for this combination, the resultant current will be the excess of that taken by the inductance over that taken by the capacity, while at frequencies above the resonant frequency, the resultant current will be the excess of that taken by the capacity over that taken by the inductance. Thus, so far as the external circuit is concerned, this combination acts like an inductance at frequencies below its resonant frequency, and like a capacity at frequencies above its resonant frequency.

If, now, we have two parallel arrangements of inductance and capacity, in series with each other, the resonant frequency of the two arrangements being different, the action, at frequencies between these resonant frequencies, so far as the voltages across the individual arrangements and the current in the external circuit are concerned, is the same as with an inductance and a capacity in series.

Considering the effect of the impressed alternating voltage upon an inductance and a capacity in series, we find the same current in both, while the voltages across the inductance and the capacity are in opposition to each other. The voltage impressed upon the combination is the resultant, or the arithmetic difference between these two voltages. With constant current in this circuit, the voltage across the inductance is proportional to the frequency, while that across the capacity is inversely proportional to it. The resonant frequency is that frequency at which these voltages are equal to each other. With any finite voltage across the combination it is seen that the resonant frequency would result in infinite voltages across the separate elements of inductance and capacity, except for the effects of losses which exist within the inductance and capacity, which will not be described here. The current, however, which can be supplied by the generator or the line, is limited, and since the voltages across the inductance and the capacity are fixed by the current, the resultant of these two equal and opposite finite voltages would be zero. This combination, at its resonant frequency, acts therefore like a short circuit. At frequencies lower than the resonant frequency for this combination, the voltage across the capacity will be greater than that across the inductance, while at frequencies higher than the resonant frequency, the voltage across the inductance will be greater. This combination will therefore act like a capacity at frequencies below its resonant frequency, and like an inductance at frequencies above that frequency.

In various types of windings, as stated above, we find capacity distributed with the inductance in various ways. There is not only capacity to ground, as represented in transformers by the core and case, but also capacity between parts of the winding, and in transformers capacity to the opposite winding. The capacities between portions of the same winding are capacities in parallel with the inductances of those portions. Also the capacities to ground, in the case of a winding which possesses a fixed ground or definite neutral point, are in parallel with the inductances between the points where the capacities are located and the ground or neutral point. We have, therefore, various parallel combinations of inductance and capacity in series with various other such combinations, which gives opportunities for resonance and excessive internal voltages at various points within the winding, occurring respectively at different frequencies.

We will now consider the effects of a sudden or abrupt voltage impressed upon typical combinations of inductance and capacity. In the case of a simple capacity, the current at the first instant is limited only by the external or supply circuit. Since current cannot be built up instantly in supply circuits which we have to consider, on account of their inductance, the voltage across the condenser will start at zero, at the first instant, and as the condenser becomes charged it will build up to the full value, and current will cease. At the first instant it acts like a short circuit, but in its final state like an open circuit.

With a simple inductance, the action will be just the reverse of that with the capacity. The current, at the first instant, will be zero, with the full value of voltage, but ultimately the current is limited by the supply circuit only, and the voltage across the inductance is zero. At the first instant the inductance acts like an open circuit, but in its final state like a short circuit.

With an inductance and capacity in parallel, the combination acts like a short circuit, at the first instant, due to the presence of the condenser, and in its final state, it acts like a short circuit, due to the presence of the inductance. During the intermediate period a certain voltage will grow, and then disappear, due to the combined action of the capacity and the inductance, but this voltage will never reach the value which would appear with an open circuit, since current exists during this period in both the inductance and the capacity.

With an inductance and capacity in series, the combination

acts like an open circuit, both at the first instant, because current cannot flow instantly through the inductance, and in its final state, because current cannot flow continuously through the capacity. At the first instant, the total voltage is across the inductance, while in the final condition, it is all across the capacity. During the interval between the first instant and the final condition, an oscillation takes place, with a maximum voltage across the inductance equal to the impressed voltage, and a maximum voltage across the capacity of double that value.

A combination such as is found in windings, as described above; namely, various parallel arrangements of inductance and capacity in series with other parallel arrangements, will act like a short circuit at the first instant, on account of the existence of the series of condensers across the entire combination. It will also act like a short circuit in its final state, on account of the series of inductances. During the intermediate period, the voltage across the combination will grow and then disappear in a manner similar to that mentioned above for a single inductance in parallel with a single capacity. If the various capacity units in this arrangement are in inverse proportion with the respective inductance units with which they are in parallel, the voltage will at all times be uniformly distributed throughout the inductance. That is, the voltage across the various inductance units will be proportional to the respective amounts of inductance, and in inverse proportion to the amounts of capacity. This result is produced with a current flowing through the series of inductances, with the same value in all, and another distinct current flowing through the series of condensers, with the same value in all.

If the capacities and inductances are not in the proportions specified above, the uniform distribution of voltage will not exist, but oscillatory disturbances will be set up which are similar in a general way to those produced by the capacity and inductance in series, due to the fact that, since currents cannot flow at the same time through the inductances with the same value in all and through the condensers with the same value in all, currents which flow through inductance in one part of the combination must flow through capacity in another part. The exact nature of the oscillation produced depends upon the particular combination of inductance and capacity which is found, and would need investigation for the particular case.

If consecutive voltages, or changes in voltage, be impressed

upon the combination of inductance and capacity found in a winding, the resulting oscillations are superposed upon each other. It is clear, therefore, that excessive voltages may be built up by a series of such voltage changes or wave fronts, occurring at intervals corresponding to a resonant frequency of the particular combination of inductance and capacity. Such a series of waves would, in fact, constitute a wave train of the resonant frequency for this combination.

While the distribution of capacity with inductance in transformer windings is ordinarily too complicated to be accurately expressed in simple terms for mathematical analysis, yet windings may be divided into two general classes, which are roughly represented by simple typical arrangements, and an investigation of the behavior of these simplified arrangements of inductance and capacity will give us a very satisfactory conception of the behavior of the two types of windings. We will now proceed to investigate in some detail these two classes of windings, which are:

1. Windings in which inductance and capacity are practically uniformly distributed.

2. Windings in which the capacity is more or less concentrated and localized at certain places in the winding, the intervening portions of the winding constituting relatively concentrated inductances.

There is no definite line of division between these two classes, since, if the individual portions of inductance and capacity are relatively small, and the frequency relatively low, the latter type of winding will act like the former type, in accordance with the principle by which a telephone line loaded with inductance coils at sufficiently frequent intervals acts like a line with uniformly distributed inductance with respect to telephone currents, which have a wave length sufficiently great that several of the loading coils occur within the length of a half wave in the line. The classification as to behavior of any given winding depends, therefore, upon the frequency of the disturbance that is considered.

A winding consisting of a single cylindrical layer is the simplest example of the first type mentioned above, while the second is represented by a winding consisting of groups of pancake coils interlaced with the coils of a low-voltage winding, which will here be considered as ground. We will first consider the behavior of:

Windings with Inductance and Capacity Uniformly Distributed. A wave arriving from the line at the terminals of a winding of this type will be partially reflected and partially propagated into and through the winding. It will produce no internal oscillation, but will merely pass along the winding, with velocity reduced and voltage increased from those found in the line. The tendency of both of these effects is to produce a steeper wave front in the winding than that found in the line, with correspondingly large transient voltages between turns. If the wave front is steep, however, there is, on the other hand, a very important opposite tendency to reduce the voltages between turns due to the capacity between turns.

If we consider, for instance, the effect of a sheer wave front arriving at the terminals of such a winding, the distribution of voltage, at the first instant, will depend upon the distribution of capacity from the first turn to ground. Referring to Fig. 1, which represents the type of winding considered, it is seen that this capacity is represented by a series of condensers between adjacent turns, with the capacity of each turn to ground shunting the part of the system beyond that turn.

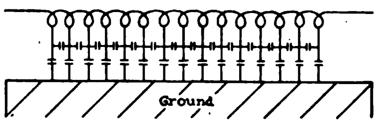


FIG. 1
Diagram of capacity and inductance in winding with uniformly distributed capacity

This combination of capacities is the same as that investigated by Mr. F. W. Peek, in his paper on "Electrical Characteristics of the Suspension Insulator," TRANSACTIONS of A.I.E.E., Vol. 31, Part I, pages 907-930. If the capacities between turns are large as compared with the capacities of the individual turns to ground, and this is the condition found in practise, the total voltage, at the first instant, is distributed by the action of the system of condensers over a considerable number of turns. Although the maximum voltage will be found on the first turn, this will be a small percentage of the total voltage, and smaller, the larger the capacities from turn to turn. This indicates a disadvantage of extra end-turn insulation, which reduces the capacity between turns, and thereby increases the transient voltages which may occur between turns.

The waves entering this winding will traverse it and be reflected in it in much the same manner as in a transmission line. A reflection point corresponding to the closed end of a line will be found at the middle of the winding for single-phase or

delta-connected transformers, with conjugate half waves arriving at opposite terminals at the same time, or at the further end for Y-connected transformers with grounded neutral. A reflection point corresponding to the open end of a line will be found at the middle of the winding for single-phase or delta-connected transformers with half waves of the same polarity arriving at opposite terminals at the same time.

With a wave train of given frequency entering the windings the position and character of the reflection point fixes the location of the nodes of the resulting standing wave train. Neglecting the effect of internal losses, this also determines the ratio of the resulting internal voltages to those existing in the line. This relation is illustrated in Figs. 2A, 2B and 2C, which represent standing waves of voltage in the winding in their relations

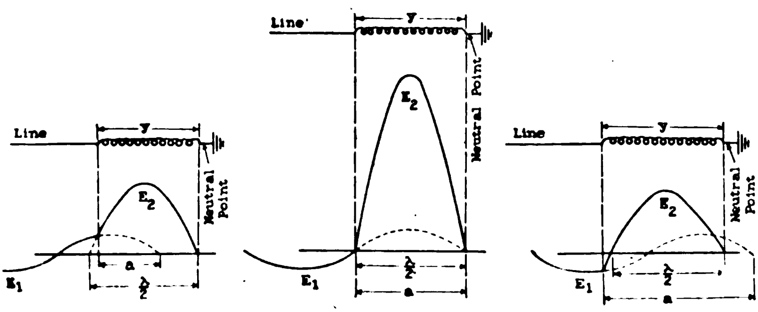


FIG. 2A FIG. 2B FIG. 2C

Standing waves of voltage in winding with uniformly distributed capacity, as related to standing waves in the line, for different values of $\frac{y}{\lambda} \cdot \frac{Z_2}{Z_1} = 10$.

to the standing waves in the line. Referring to these figures, we call the maximum value of voltage in the line E_1, and that in the winding E_2. The length of the winding from the entrance to the reflection point is y, and the wave length within the winding λ. Then, from the figures, we derive the equation

$$\frac{E_2}{E_1} = \frac{1}{\sqrt{\sin^2 2\pi \frac{y}{\lambda} + \left(\frac{Z_1}{Z_2}\right)^2 \cos^2 2\pi \frac{y}{\lambda}}} \qquad (1)$$

where Z_1, and Z_2 are the wave impedances respectively of the lines and the winding. Z_1 and Z_2 are further defined by the equation $Z_1 = \sqrt{\frac{L_1}{C_1}}$ and $Z_2 = \sqrt{\frac{L_2}{C_2}}$, where L_1 and C_1 are respec-

tively the inductance and the capacity per unit length of the line, and L_2 and C_2 the effective inductance and the effective capacity per unit length of the winding. This equation is derived as follows:

The number of wave lengths between the reflection node and the entrance to the winding is $\frac{y}{\lambda}$, and a is the fraction of a wave length between the entrance and what would be the next node of same character as the reflection node, if the line were continuous. Let E and I be the voltage and current at the entrance, which are common to the line and the winding. Then, remembering that voltage nodes are current antinodes, and *vice versa*, we may write

$$E = E_2 \sin 2\pi \frac{y}{\lambda} = E_1 \sin a \tag{2}$$

and

$$I = I_2 \cos 2\,\pi \frac{y}{\lambda} = I_1 \cos a \tag{3}$$

or, since $$I_1 = \frac{E_1}{Z_1} \text{ and } I_2 = \frac{E_2}{Z_2}\,* \tag{4}$$

$$I = \frac{E_2}{Z_2} \cos 2\pi \frac{y}{\lambda} = \frac{E_1}{Z_1} \cos a$$

whence, by the relation $\cos = \sqrt{1 - \sin^2}$, we have

$$\sin^2 a = 1 - \left(\frac{E_2\, Z_1}{E_1\, Z_2} \cos 2\,\pi \frac{y}{\lambda}\right)^2 \tag{5}$$

From (2) we have

$$\frac{E_2}{E_1} = \frac{\sin a}{\sin 2\,\pi \frac{y}{\lambda}} \tag{6}$$

*See discussion on "Some Simple Examples of Transmission Line Surges," page 1641 of A.I.E.E. PROCEEDINGS, October, 1914.

Substituting sin a from (**5**) and simplifying, we get equation (**1**).

The way in which the internal voltages build up to the values shown in the figures and represented by equation (**1**) is explained as follows: With respect to the first wave of a traveling wave train, the transformer winding will act practically as open circuit to the line, regardless of the length of y, on account of the small amount of current admitted. That is, a voltage antinode and current node will be produced in the line at the entrance. Concentrating our attention upon figure 2B with $y = \frac{\lambda}{2}$, we find that the internal reflection will produce a voltage node at the entrance. The succeeding wave will therefore find as free admission as the first, and its current will be superposed upon that of the internal standing wave already produced. This process will continue, admitting more and more current from the line with each succeeding wave, until the current node found at first in the line at the entrance becomes an antinode, while the voltage antinode is reduced to a node.

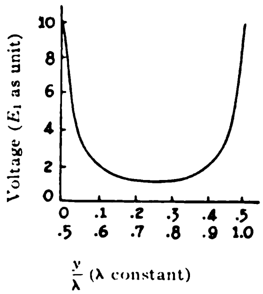


FIG. 3

Maximum voltage in winding with uniformly distributed capacity, as affected by the ratio of winding length to wave length, $\frac{y}{\lambda}$, in terms of the maximum standing wave voltage in the line. Plotted from equation (**1**), with $\frac{Z_1}{Z_2}$ = 10.

For the particular case represented by figure 2B, which gives the maximum internal voltage, since $y = 1/2\ \lambda$, equation (**1**) simplifies to the form

$$\frac{E_2}{E_1} = \frac{Z_2}{Z_1} \text{ (for } y = 1/2\ \lambda) \qquad (\mathbf{7})$$

The current in the winding is the same as the current in the line and the voltages are proportional to the respective wave impedances. Equation (**7**) holds for values of y such that $y = 1/2\ \lambda$ or any multiple thereof.

The maximum internal voltage which could be produced is plotted in Fig. 3 in terms of the external standing wave voltage E_1, for the ratio $\frac{Z_2}{Z_1} = 10$, with y varying between 0 and $\frac{1}{2}\ \lambda$. This curve repeats itself for the ranges of y between $\frac{1}{2}\ \lambda$ and λ.

between λ and $1\frac{1}{2}$ λ, etc. The minimum value for these voltages found for y equal $\frac{1}{4}$ λ or any odd multiple thereof, is

$$\frac{E_2}{E_1} = 1 \text{ (for } y = 1/4\ \lambda) \tag{8}$$

It is worthy of note that for values of $\frac{y}{\lambda}$ varying between 0 and $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$, etc., the current taken by the winding from the line lags 90 deg. in time behind the voltage at the transformer terminals, whereas for values between $\frac{1}{4}$ and $\frac{1}{2}$, $\frac{3}{4}$ and 1, etc., the current leads the voltage by 90 deg. That is, in the former cases the winding acts like an inductance, and in the latter like a capacity.

It should be noted, that, though the wave lengths as represented in the figures are the same in the winding as in the line, this is not true in ordinary linear measure. The linear relation between wave lengths is found as follows: The relation between frequency, velocity and wave length is

$$f = \frac{v}{\lambda} \tag{9}$$

where the velocity is

$$v = \frac{1}{\sqrt{L\,C}} \tag{10}$$

and L and C are the inductance and the capacity per unit length of the circuit. Since the frequency is the same for the line and the winding, using the subscripts 1 and 2 for the line and the winding respectively, we have

$$\lambda_2 = \frac{\sqrt{L_1\,C_1}}{\sqrt{L_2\,C_2}}\ \lambda_1 \tag{11}$$

The effect of frequency upon the internal voltages will become more obvious if we substitute in equation (1) the value of λ in terms of frequency, and inductance and capacity per unit length of the winding. This is

$$\lambda = \frac{1}{f\sqrt{L_2 C_2}} \tag{12}$$

The substitution gives

$$\frac{E_2}{E_1} = \frac{1}{\sqrt{\sin^2 2\,\pi\, f\, y\,\sqrt{L_2\,C_2} + \left(\frac{Z_1}{Z_2}\right)^2 \cos^2 2\,\pi\, f\, y\,\sqrt{L_2\,C_2}}} \quad \textbf{(13)}$$

We must still consider, moreover, the effects of frequency upon L_2 and C_2, since, at high frequencies, the effective inductance and the effective capacity per unit length of the winding are affected by the frequency.

The turn to turn capacity between positive and negative half waves becomes important at high frequencies, on account of the proximity of the half waves. This capacity has the same effect upon velocity, wave length, wave impedance and voltage as twice the same amount of capacity to ground, and must therefore be added to the capacity to ground at double value.

The increase in total effective capacity per unit length with increased frequency, due to this cause, is all the greater on account of its reflex action. By reducing the velocity of propagation, it brings the half waves still closer together, with consequent further increase in effective capacity.

On the other hand, the effective inductance per unit length of the winding will be reduced by increased frequency. This is due to the fact that the part of the winding which acts as a unit with respect to inductance is reduced by the shorter wave length. This effect is illustrated by Nagaoka's table of correction factors for inductance calculated for a single layer coil by the formula for a long solenoid. This table, given in " Calculation of Alternating Current Problems " by Cohen, pages 80 and 81, gives correction factors varying from unity for the infinitely long solenoid to 0.2 for a coil of length 0.1 as great as its diameter.

This reduction in inductance with increased frequency will tend to neutralize the effect of increased capacity upon the velocity of propagation, but augments its effect upon the wave impedance of the winding. If we assume that the factor by which the capacity is increased is the same as the factor by which the inductance is decreased, the sine and cosine terms in equation (**13**) will not be affected, the only effect upon the internal voltages due to the variations in capacity and inductance with frequency being that which appears in the factor $\left(\frac{Z_1}{Z_2}\right)^2$, which may be written $Z_1^2\,\frac{C_2}{L_2}$.

Where L_w and C_w are the total inductance and capacity of the winding measured at normal operating frequency, if we assume that the wave impedance of the winding is $\sqrt{\frac{L_w}{C_w}}$ for the frequency $f = \frac{1}{\sqrt{L_w C_w}}$, which gives a $\frac{1}{2}$ wave length within the winding, and if we assume further that, due to the changes in inductance and capacity, the wave impedance is inversely proportional to the square root of the frequency,* we may write, for any frequency,

$$Z_2^2 = \frac{L_2}{C_2} = \frac{1}{2 f \sqrt{L_w C_w}} \frac{L_w}{C_w} \tag{14}$$

We have also, when y is the total length of the winding

$$y \sqrt{L_2 C_2} = \sqrt{L_w C_w} \tag{15a}$$

and when y is $\frac{1}{2}$ of the length of the winding

$$y \sqrt{L_2 C_2} = \frac{\sqrt{L_w C_w}}{2} \tag{15b}$$

Substituting (**14**) and (**15a**) in (**13**) we obtain

$$\frac{E_2}{E_1} = \frac{1}{\sqrt{\sin^2 2\pi f \sqrt{L_w C_w} + \frac{2 Z_1^2 f C_w^{3/2}}{L_w^{1/2}} \cos^2 2\pi f \sqrt{L_w C_w}}} \tag{16a}$$

or from (**14**) and (**15b**)

$$\frac{E_2}{E_1} = \frac{1}{\sqrt{\sin^2 \pi f \sqrt{L_w C_w} + \frac{2 Z_1^2 f C_w^{3/2}}{L_w^{1/2}} \cos^2 \pi f \sqrt{L_w C_w}}} \tag{16b}$$

The internal voltages in terms of the line voltage, in accord-

*This is equivalent to the assumption that L_2 is inversely and C_2 directly proportional to the square root of the frequency.

ance with equations (**16**), are plotted in Fig. 4, for the assumed values of

$$Z_1 = 490 \text{ ohms}$$
$$C_w = 0.00248 \text{ mf.}$$
$$L_w = 0.175 \text{ henrys}$$

The effects of losses within the transformer winding were not taken into account in the above derivations. The dielectric losses at high frequency and high voltage are high, and cause a rapid damping of the entering wave train as it traverses the winding. The outgoing wave being smaller than the incoming one, this gives a combination of traveling waves and standing waves,

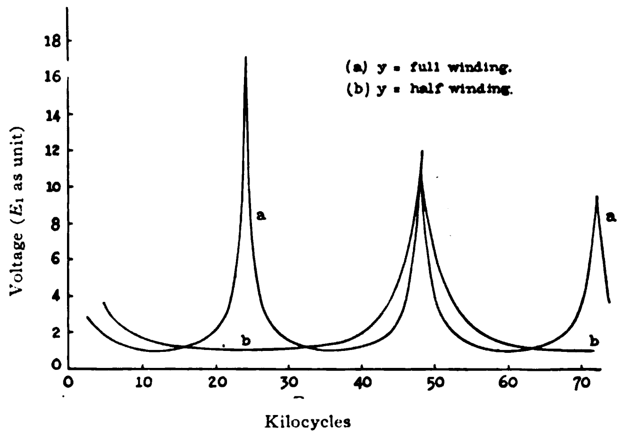


FIG. 4

Effect of frequency upon the maximum voltage in winding with uniformly distributed capacity, in terms of the maximum standing wave voltage in the line. Plotted from equation (**16b**), with $Z_1 = 490$ ohms, $L_w = 0.175$ henry and $C_w = 0.00248$ m.f.

the standing waves being smaller the greater the damping. This not only prevents the internal voltages from building so high, but throws them out of phase with each other. With a true standing wave train, all voltages are in the same time phase, and either add or subtract numerically, but voltages measured between points equally distant in the winding have every value from zero to maximum. With a pure undamped traveling wave, the same voltage may be measured between points equally distant in the winding, but all phase relations are found. With traveling waves superposed upon standing waves, we find both varying voltages and varying phase relations between equidistant

points. This is what we will expect to find in a transformer winding of this type, the voltages being most nearly in phase near the node of reflection, where the standing waves predominate and furthest out of phase, but almost nearly equal, between equidistant points near the entrance, where the traveling wave component is maximum.

Winding With Capacity More or Less Concentrated and Localized. A winding consisting of groups of pancake coils interlaced with a low-voltage winding is represented by the simplified arrangement of capacity and inductance in Fig. 5. If the middle of this winding is grounded, or a neutral point, the middle capacity C_3 is short circuited. Neglecting the capacities C_1 and C_5, adjacent to the line, which exist also with the winding with distributed capacity considered above, and also neglecting the turn-to-turn and coil-to-coil capacities, which are in parallel with the respective inductances, we will consider a disturbance

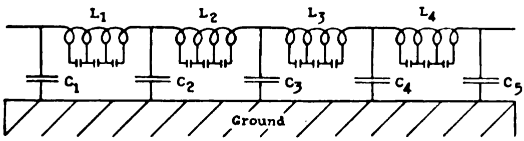
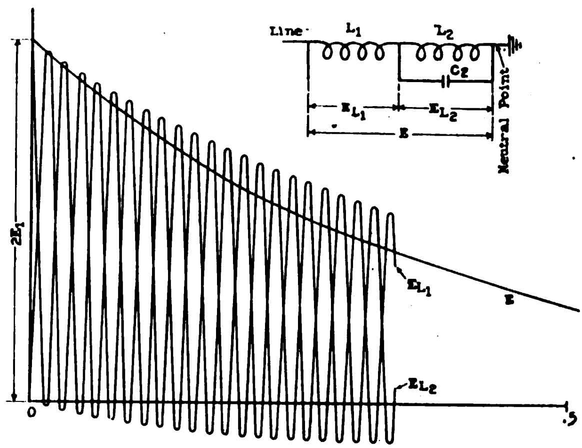


FIG. 5
Diagram of capacity and inductance in winding with localized capacity.

entering this winding from one end. We find between the line and neutral, or ground, the inductance L_1 in series with the parallel arrangement of inductance L_2 and capacity C_2. Any other location of neutral point or ground, as with one end of the winding grounded, will give a more complicated arrangement of inductance and capacity between this point and the line. The behavior of such combinations is, however, based upon the same principles as those which we will consider in detail in connection with this most simple arrangement.

An impulse or wave of sufficiently short duration impinging upon this combination would be practically unfelt beyond the inductance L_1, since the current in the inductance would be zero at the first instant, and current must flow to charge the capacity C_2. If the inductances and capacities were distinct concentrated quantities, as assumed, the voltage of this wave would be uniformly distributed between the turns of inductances L_1. There is, however, a certain amount of capacity to ground distributed

with the inductance. In fact, a large part of the capacities shown concentrated in the figure are distributed near the ends of the inductances. This would effect the concentration of the voltage of an abrupt wave front over a very small number of turns, and in the ultimate conceivable limit, with a perfectly sheer wave front, over a single turn, if it were not for the fact that we have also capacities between turns. As in the winding already considered, these capacities between turns always effect the distribution of an abrupt voltage over a considerable number of turns, the voltage between adjacent turns being smaller, the larger the capacity between turns.



Time in milliseconds

FIG. 6

Voltage oscillations set up by a traveling wave with abrupt front, in a winding with capacity localized as shown in the sketch. Plotted from equations (86a) and (87a), with $Z_1 = 490$ ohms, $L_1 = L_2 = 0.1$ henry and $C_2 = 0.0005$ m.f.

With a wave of considerable duration, an oscillation is produced, which is investigated mathematically in an appendix to this paper, the resulting voltages across L_1 and L_2 being plotted in Fig. 6 for the values $L_1 = L_2 = 0.1$ henry, $C_2 = 0.0005$ mf. and $Z_1 = 490$ ohms.

If a wave of opposite polarity from the first one appears at the terminals of the winding at the end of the first or any odd numbered half cycle of the oscillation due to the first wave front shown in Fig. 6, a new oscillation will be superposed upon the first one in phase with it, with a corresponding increase in amplitude. With no damping in the winding, the amplitude of the

voltages which might be built up in this manner by a succession of wave fronts of opposite polarity, so timed as to be in resonance with the oscillations of the winding, depends upon the current supplied by the line. The reflection of the first wave at the transformer terminal produces a voltage antinode and current node at the entrance of the winding. As the resonant voltages build up across the parts of the winding, the high frequency current taken by the winding increases, gradually changing the voltage antinode and current node at the entrance to a voltage node and current antinode. This supplies the maximum current which can be delivered by the line and consequently limits the resonant voltages produced.

The frequency of the oscillations expressed in equations (**36**) and (**37**) of the appendix, and represented in Fig. 6, at which resonant voltages may be built up as described above, is the same as the frequency of resonance which would be calculated from the ordinary impedance equations. Thus, for the parallel combination of L_2 and C_2, at frequencies above its resonant frequency, the equivalent capacity impedance is (writing w for $2\,\pi\,f$).

$$\frac{1}{w\,C'} = \frac{1}{w\,C_2 - \dfrac{1}{w\,L^2}} = \frac{w\,L_2}{w^2\,L_2\,C_2 - 1} \qquad \textbf{(17)}$$

This equivalent capacity resonates with the series inductance L_1 at a frequency giving

$$wL_1 = \frac{1}{wC'} \qquad \textbf{(18)}$$

and from equations (**17**) and (**18**) we obtain

$$w = \sqrt{\frac{L_1 + L_2}{L_1\,L_2\,C_2}} \qquad \textbf{(19)}$$

Or, when $L_1 = L_2$ dropping subscripts

$$w = \sqrt{\frac{2}{LC}} \qquad \textbf{(20)}$$

This is the value of c in equations (**36b**) and (**37b**) as shown in (**36a**) and (**37a**) of the appendix, and the frequency found in the oscillations of Fig. 6 is

$$f = \frac{1}{2\pi}\sqrt{\frac{2}{LC}} \tag{21}$$

Assuming that L_1, L_2 and C_2 are not affected by frequency, and neglecting the internal losses of the winding, we may calculate the maximum voltages which would be produced by a sustained wave train of any frequency. As with the winding with uniformly distributed capacity, we will call maximum standing wave voltage and current in the line E_1 and I_1 and voltage and current at the entrance of the winding E and I. As in equations (**2**) and (**3**)

$$E = E_1 \sin a \tag{22}$$

and

$$I = I_1 \cos a \tag{23}$$

"a" being the fraction of a wave length in the line from the entrance of the winding to what would be a nodal point corresponding to a short circuited line. In the winding the voltage E must force the current I through the impedance

$wL_1 + \dfrac{wL_2}{1 - w^2 L_2 C_2}$, so that

$$E_1 = I\left(w\,L_1 + \frac{wL_2}{1 - w^2\,L_2\,C_2}\right) \tag{24}$$

Substituting (**22**) and (**23**) this gives

$$E_1 \sin a = I_1 \cos a\left(wL_1 + \frac{wL_2}{1 - w^2\,C_2\,L_2}\right) \tag{25}$$

whence

$$\tan a = \frac{1}{Z_1}\left(wL_1 + \frac{wL_2}{1 - w^2\,L_2\,C_2}\right) \tag{26}$$

Having found a, the voltages across L_1 and L_2 are

$$E_{L_1} = I_1 \cos a \, wL_1 \text{ (max. value)} \tag{27}$$

and

$$E_{L_2} = I_1 \cos a \frac{wL_2}{1 - w^2 L_2 C_2} \text{ (max. value)} \tag{28}$$

Or, in terms of the maximum voltage in the line,

$$\frac{E_{L_1}}{E_1} = \frac{wL_1}{Z_1} \cos a \tag{29}$$

and

$$\frac{E_{L_2}}{E_1} = \frac{wL_2}{Z_1 (1 - w^2 L_2 C_2)} \cos a \tag{30}$$

The gradient of maximum instantaneous voltage within the winding, and the standing wave voltage in the line, in accordance with equations (**26**), (**29**) and (**30**), are shown in Fig. 7 for the values

$$Z_1 = 490 \text{ ohms}$$
$$L_1 = L_2 = 0.1 \text{ henry}$$
$$C_2 = 0.00Q5 \text{ mf.}$$

and for various values of frequency selected with view to illustrating its effect upon internal voltages. L_1, L_2 and C_2 are assumed to be constant independent values (not affected by frequency). A feature of incidental interest appears in the location of the voltage node (current antinode) in the line with respect to the entrance to the winding.

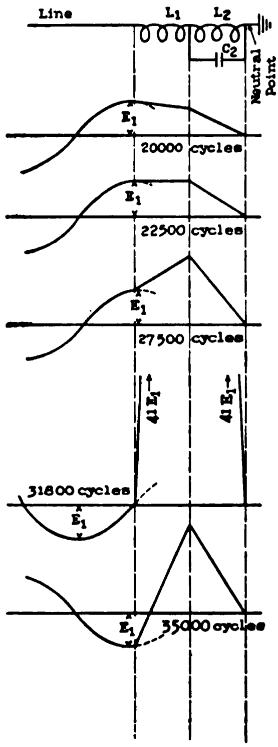


FIG. 7
Voltages in winding with capacity localized as shown, as related to the standi g waves in the line, for different frequencies. Calculated from equations (**29**) and (**30**), with Z_1 = 490 ohms, $L_1 = L_2$ = 0.1 henry and C_2 = 0.0005 mf.

We find the voltage antinode exactly at the entrance to the winding at the frequency at which L_2 and C_2 are in resonance with each other. This, for the value of inductance and capacity used, is

$$f = \frac{1}{2\pi\sqrt{L_2 C_2}} = 22{,}500 \text{ cycles.}$$

Below this frequency this parallel combination acts like an inductance, of value increasing as the frequency increases and reaching infinity

$$\frac{wL_2}{1 - w^2{}_{L^2 C_2}} = \frac{wL_2}{0} = \infty \qquad \textbf{(31)}$$

at this resonant frequency. Above this frequency it acts like a capacity, of value increasing from zero at resonant frequency to the limiting value C_2 at very high frequencies.

Below the frequency $f = \frac{1}{2\,\pi\,\sqrt{L_2\,C_2}}$ the total arrangement L_1, L_2 and C_2 acts as an inductance, the inductive impedance $\frac{wL_2}{1 - w^2\,L_2\,C_2}$ being in series with $w\,L_1$. The voltage E_{L_1} and E_{L_2} are in phase with each other, the value of the former diminishing to zero at this frequency, where the infinite impedance $\frac{wL_2}{1 - w^2\,L_2\,C_2} = \infty$ acts like open circuit. Between this frequency and the resonant frequency $f = \frac{1}{2\,\pi}\sqrt{\frac{L_1 + L_2}{L_1\,L_2\,C_2}}$ at which the voltage node appears at the terminals, the total arrangement acts like a condenser, with value increasing from zero at the lower frequency to infinity at the higher frequency. The voltages E_{L_1} and E_{L_2} are in phase opposition, the voltage at the winding terminals being equal to their difference. The voltage E_{L_1} grows from zero value at the lower frequency to a value limited by the maximum value of current in the line at the higher frequency. The voltage E_{L_2}, which is the capacity or leading voltage, is greater than the voltage E_{L_1} by the amount of the voltage in the line at the winding terminals. Above the frequency $f = \frac{1}{2\,\pi}\sqrt{\frac{L_1 + L_2}{L_1\,L_2\,C_2}}$ the voltages E_{L_1} are E_{L^2} and still in phase opposition, but the voltage E_{L_1} is larger than E_{L_2} by the amount of the voltage at the winding terminals, and the total arrangement is acting like an inductance, increasing from zero to the limiting value L_1. At very high frequencies the voltage E_{L_2} becomes very small, the voltage E_{L_1} being practically equal to the voltage in the line.

The variations in these internal voltages with the frequency, and that of the voltage across the total combination, are shown in the curves of Fig. 8.

We have discussed in detail the behavior of the arrangement L_1, L_2 and C_2. If the same winding (Fig. 5) were grounded at one end, or at some other point not the middle, or if a winding of more than four groups (six for instance) were grounded at the middle, assuming a simplification of the distribution of capacity such as shown in Fig. 5, there would still be a more complicated arrangement than the one we have considered. As already stated however, the same general principles would be involved in the behavior of any such arrangement. Detailed discussion is not

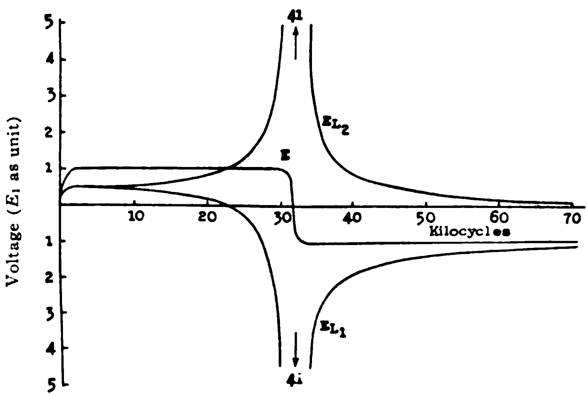


FIG. 8

Effect of frequency upon voltages in winding with capacity localized as shown in Figure 7, in terms of the maximum standing wave voltage in the line. Plotted from equations (29) and (30), with Z_1 = 490 ohms, $L_1 = L_2 = 0.1$ henry, and C_2 = 0.0005 mf.

given therefore, to any other such arrangement, but, by way of further illustration of what may occur, we give in Fig. 9 a set of diagrams similar to those of Fig. 7, showing the relation of internal voltages to the line voltage at various selected frequencies, with three groups of coils (three units of inductance, with intervening capacities) between the line and a grounded or neutral point. The equations for this case, to which these diagrams correspond, are,

$$\tan a = \frac{1}{Z_1}\left[wL_1 + \frac{w(L_2 + L_3) - w^3 L_2 L_3 C_3}{1 - w^2 (L_2C_2 + L_3C_3 + L_3C_2) + w^4 L_2 L_3 C_2 C_3}\right] \quad (32)$$

$$\frac{E_{L_1}}{E_1} = \frac{1}{Z_1} wL_1 \cos a \tag{33}$$

$$\frac{E_{L_2}}{E_1} = \frac{1}{Z_1} \frac{wL_2 - w^3 L_2 L_3 C_3}{1 - w^2 (L_2 C_2 + L_3 C_3 + L_3 C_2) + w^4 L_2 L_3 C_2 C_3} \cos a \tag{34}$$

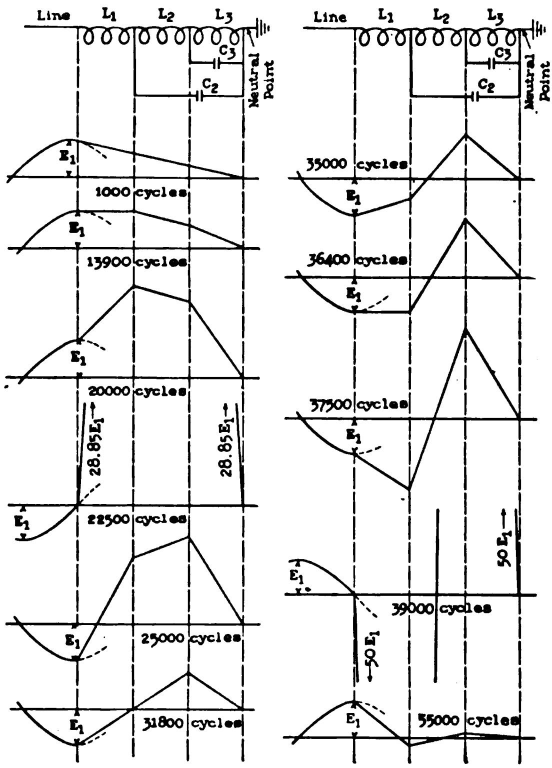


FIG. 9

Voltages in winding with capacity localized as shown, as related to standing waves in the line, for different frequencies. Calculated from equations (**37**), (**38**) and (**39**), with Z_1 = 490 ohms, $L_1 = L_2 = L_3$ = 0.1 henry and $C_2 = C_3$ = 0.0005 mf.

and

$$\frac{E_{L_3}}{E_1} = \frac{1}{Z_1} \frac{wL_3}{1 - w^2 (L_2 C_2 + L_3 C_3 + L_3 C_2) + w^4 L_2 L_3 C_2 C_3} \cos a \tag{35}$$

With all inductance units equal and all capacity units equal we drop the subscripts and write:

$$\tan a = \frac{1}{Z_1} \frac{3wL - 4w^3 L^2 C + w^5 L^3 C^2}{1 - 3w^2 LC + w^4 L^2 C^2} \qquad (36)$$

$$\frac{E_{L_1}}{E_1} = \frac{1}{Z_1} w L \cos a \qquad (37)$$

$$\frac{E_{L_2}}{E_1} = \frac{1}{Z_1} \frac{wL - w^3 L^2 C}{1 - 3w^2 LC + w^4 L^2 C^2} \cos a \qquad (38)$$

and

$$\frac{E_{L_3}}{E_1} = \frac{1}{Z_1} \frac{wL}{1 - 3w^2 LC + w^4 L^2 C^2} \cos a \qquad (39)$$

Several cases of resonance, at different frequencies, are found in these diagrams. It will be noticed that high voltages occur across some of the inductance units, at different frequencies, but not always across all at the same frequency. The variations in the internal voltages of this combination with the frequency are shown in Fig. 10.

As with the winding of distributed capacity, the damping due to the internal losses prevents the building up of the excessive voltages found above. These voltages can be built up only by the admission of small amounts of energy by the inductance L_1 from the successive wave fronts of a high-frequency train. The dielectric losses in the winding increase as the voltage builds up, until the energy absorbed is equal to the energy admitted. These losses are even higher in windings of this type than in those with distributed inductance and capacity, and probably restrict the voltages to a small fraction of those found above.

It has already been mentioned that in any case a certain amount of capacity will be found distributed with the inductances L_1, L_2, etc. It is obvious, therefore, that at frequencies sufficiently high, these parts of this winding may behave in a manner somewhat similar to the winding with distributed inductance and capacity. That is, standing waves may be set up within the individual coils or groups of the winding. Frequencies giving these results are produced by discharges at or near the terminals of the transformer, and such discharges produce the most dangerous condition with respect to the insulation between turns. On the other hand, the most dangerous condition with respect to the

insulation between the winding and ground (low-voltage winding and core) is produced by the frequencies producing resonance between groups. The frequencies producing dangerous voltages between turns are much higher than these.

Effects of Normal Frequency Currents and Voltages. No consideration has been given in the foregoing discussions to the effects of the normal voltages and currents existing in the windings of the transformer before the arrival of the steep wave front and the high frequency wave train. A statement of the principle

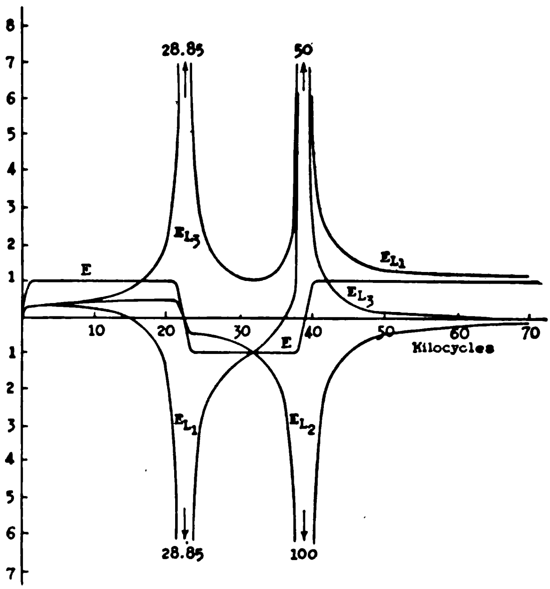


FIG. 10

Effect of frequency upon voltages in winding with capacity localized as shown in Figure 9, in terms of maximum standing wave voltage in the line. Plotted from equations (37), (38) and (39), with Z_1 = 490 ohms, $L_1 = L_2 = L_3 =$ 0.1 henry and $C_1 = C_2 =$ 0.005 mf.

facts involved will be sufficient answer for the questions arising in this direction.

It is evident that the distribution of voltage in a circuit or winding can not be disturbed or altered by the flowing of currents of equal value throughout the entire circuit, or by any changes in current which occur uniformly throughout the entire circuit, so that at any given instant the same value of current flows at every point in the circuit. Even the normal variations of voltage within a transformer winding having capacity are accompanied

by the flow of charging currents which traverse only portions of the winding to supply the charges corresponding to the voltage changes of the capacity which is located within the winding. These currents are normal frequency currents, controlled by the normal flux variations which bind the charges supplied. These currents are ordinarily very small as compared with the normal frequency load or exciting currents which flow with equal value throughout the winding and upon which they are superposed.

Now the current of a traveling wave entering the winding is only that required to change the potential of the winding to correspond with the voltage of the wave. The magnitude of this current will not be affected by currents already flowing with equal value throughout the winding. Moreover, the normal frequency charging current of the winding is negligibly small as compared with that of the traveling wave and need not be considered. The wave current is merely superposed upon the previously existing current.

The wave current is still small as compared with the normal load current of the transformer, so that if a transformer is loaded, the entrance of the first wave of an oscillation has small effect upon the actual resultant current. High frequency currents of considerable value might, as we have seen, be built up within the winding by sustained wave trains or oscillations at resonating frequencies, except for the heavy internal damping due to dielectric loss at these high frequencies and with the high accompanying voltages. Due to this damping, these currents are still relatively small. In any event they may still be looked upon as merely superposed upon the current with equal value throughout the winding, produced by the voltage impressed from normal source, although this latter current may become changed from its initial value. It does, in fact, change in normal operation, since it is an alternating current, but it may also be changed by the conditions producing the oscillation, as by short circuit, for instance. Thus, in the case of short circuit beginning with an oscillation, we have the oscillatory current superposed upon the current from the generator which has uniform value throughout the transformer winding at any instant, but which changes cyclically in time with the normal frequency of the generator, and more or less gradually from the initial to the final value.

Questions as to the effects of the initial or normally changing voltages or voltage distributions of the windings upon the

voltages set up by waves and oscillations have already been answered implicitly in the above discussion of the effects of currents, on account of the perfectly definite relation between voltages and currents in any circuit with respect either to steady or gradually changing conditions or to oscillations. The statement may be made general, therefore, with respect to both voltage and current, that the initial current and voltage of the transformer will have no effects upon the results of a steep wave front or high-frequency wave train except in so far as they may fix the conditions which set up the oscillation, and so determine its character, and in so far as the actual conditions of current and voltage set up are due to the superposition of the oscillatory or traveling wave currents and voltages upon a value of current and a voltage gradient which is uniform throughout the winding and which is arrived at by a process of gradual change from the initial value.

Effect of the Core and its State of Magnetization. It is necessary to consider the effect of the transformer core and its state of magnetization upon the behavior of the windings when subjected to a high-frequency disturbance. The statement of some fundamental facts will help to clear up these questions also.

The variation of the flux in the core in response to the voltage applied at normal operating frequencies, and the relation of the magnetic density to the exciting current, are well understood. It is also known that the core responds in the same general manner at high frequencies, the chief differences between the behavior at high frequency and at low frequency being the apparent reduction in permeability due to the restriction of flux from the center of the sheets by skin effect, and the increased eddy current and hysteresis losses for a given flux variation. None of these considerations are important, however, since the flux variations corresponding to any high-frequency voltage which may be impressed will always be small.

The behavior of the windings with respect to the core at high frequency will differ from that at operating frequencies in that a small part of one of the windings may act as primary with respect not only to the other winding but also with respect to the remaining part of the same winding. Moreover the portion of the winding acting as primary is variable from instant to instant. Thus if we consider a traveling wave entering the winding with distributed capacity, the first turns act

as primary with respect to all the other turns, whereas a little later the number of turns acting as primary turns will have increased. As the entering wave traverses the first part of the winding, the distributed capacity permits the setting up of reverse currents in the remaining part of the winding, as well as in the opposite winding, which correspond to a condition of short circuited secondary, even though the other windings were open circuited. The result is that the flux set up by the wave is practically all leakage flux occupying only a small portion of the core. If the wave be a long one, the secondary currents soon cease, with the charging of the available capacity, and the condition is changed from one of short circuit to one of open circuit. The flux due to the traveling wave thus comes to occupy the complete magnetic circuit of the core, resulting in a large increase in the inductance per unit length of winding. If the other winding be connected to a closed circuit, these conditions will be affected only in so far as current can be drawn from the other circuit. This requires voltage, and involves the transformation of the wave from one winding to the other.

If we consider the case of standing waves set up within the winding, the amplitude of all of the waves being the same, we will in general find a fractional excess of positive or negative half waves of current within the winding.

This gives an excess of positive or negative ampere turns which magnetizes the core, and so generates a voltage throughout the entire winding which is counter to the voltage in the line at the transformer terminals. The internal standing wave voltages are superposed upon this voltage. Within certain ranges of frequency or lengths of winding, *i.e.*, of the ratio $\frac{y}{\lambda}$, the standing wave current entering the winding is restricted and consequently the internal standing wave voltages restricted, by the condition that the distributed voltage can not exceed the standing wave voltage found in the line at the terminals of the transformer. For the frequency giving the maximum internal voltages, however, *i.e.*, with a voltage node and current antinode at the entrance, there is no such restriction, since there are equal numbers of positive and negative half waves of current within the winding.

Similar restrictions will be found with the winding in which capacity and inductance are separated into alternate more or

less concentrated amounts, but will not appear at resonant frequencies, since equal amounts of positive and negative current will be found within the inductances of the winding.

The high frequency flux set up within the core by an excess of positive or negative ampere turns generates voltages not only in the winding upon which the high frequency disturbance is impressed but also in the other winding. Charging current set up by this voltage in the second winding is in phase with the excitation, and tends to increase the voltage. Excess voltages may be thus built up in this winding at its resonant frequency.

While the transformer core no doubt has an important influence on the behavior of the windings at high frequency, this influence is not affected by its initial state of magnetization except in so far as its permeability is affected. The voltages generated by flux in the core are distributed throughout the windings, and depend in a regular manner upon the unbalanced ampere turns and the high-frequency permeability of the core, in its existing state of saturation.

Conclusion

The above analysis of the behavior of transformer windings is by no means complete, but such an examination of the fundamental facts and principles involved gives us a clearer insight into the nature of the excessive internal voltages which, as shown by experience, are produced in practise. This will enable us to guard against these voltages in a more scientific and economical manner. It is expected that this will constitute the subject of a subsequent paper.

APPENDIX

The behavior of the combination of inductance and capacity represented in Fig. 6, at the end of a transmission line, when a wave with steep front and of considerable length strikes it, is investigated as follows:

The reflection in the line is at the first instant complete, as at the open end of a line, giving double voltage and zero current. If the voltage of the original wave is E_1 and the current I_1, the reflected voltage and current at the first instant are $(E_1')_0 = E_1$ and $(I_1')_0 = -I_1$. At a subsequent instant the numerical value of the reflected current is reduced by the current flowing through the inductance L_1, and the voltage impressed on the transformer is correspondingly reduced.

The voltage at the terminals of the transformer to any instant is

$$E = E_1 + E_1' \tag{1}$$

This voltage appears across the inductance L_1 and the parallel arrangement $L_2\,C_2$, so that we also have

$$E = L_1 \frac{dI_{L_1}}{dt} + L_2 \frac{dI_{L_2}}{dt} \tag{2}$$

where I_{L_1} and I_{L_2} are the respective currents flowing in inductances L_1 and L_2.

In the line we have

$$E_1 = I_1\,Z_1 \tag{3}$$

and

$$E_1' = -\,I_1'\,Z_1 \tag{4}$$

and the current in the inductance L_1 is

$$I_{L_1} = I_1 + I_1' \tag{5}$$

so that

$$-\,I_1' = I_1 - I_{L_1}$$

This value in (**4**) gives

$$E_1' = (I_1 - I_{L_1})\,Z_1 \tag{6}$$

whence

$$E_1' = E_1 - I_{L_1}\,Z_1 \tag{7}$$

Substituting this value in (**1**) gives

$$E = 2\,E_1 - I_{L_1}\,Z_1 \tag{8}$$

and this with equation (**2**) gives

$$2E_1 = L_1 \frac{dI_{L_1}}{dt} + L_2 \frac{dI_{L_2}}{dt} + I_{L_1}\,Z_1 \tag{9}$$

Now, considering voltage in the parallel elements C_2 and L_2, we have

$$\int \frac{I_{C_2}\,dt}{C_2} = L_2 \frac{dI_{L_2}}{dt} \tag{10}$$

whence

$$I_{C_2} = C_2 L_2 \frac{d^2 I_{L_2}}{dt^2} \tag{11}$$

We also have

$$I_{C_2} + I_{L_2} = I_{L_1} \tag{12}$$

whence

$$I_{L_1} = I_{L_2} + C_2 L_2 \frac{d^2 I_{L_2}}{dt^2} \tag{13}$$

Substituting (**13**) in (**9**), and transforming.

$$\frac{d^3 I_{L_2}}{dt^3} + \frac{Z_1}{L_1} \frac{d^2 I_{L_2}}{dt^2} + \frac{L_1 + L_2}{L_1 L_2 C_2} \frac{d I_{L_2}}{dt} + \frac{Z_1}{L_1 L_2 C_2} I_{L_2}$$

$$= \frac{2 E_1}{L_1 L_2 C_2} \tag{14}$$

and substituting

$$I = I_{L_2} - \frac{2E_1}{Z_1} \tag{15}$$

we get

$$\frac{d^3 I}{dt^3} + \frac{Z_1}{L_1} \frac{d^2 I}{dt^2} + \frac{L_1 + L_2}{L_1 L_2 C_2} \frac{dI}{dt} + \frac{Z_1}{L_1 L_2 C_2} I = 0 \tag{16}$$

The solution of this equation is

$$I = A_1 e^{x_1 t} + A_2 e^{x_2 t} + A_3 e^{x_3 t} \tag{17}$$

x_1, x_2 and x_3 being the root s cf tł e auiary equation.

$$x^3 + \frac{Z_1}{L_1} x^2 + \frac{L_1 + L_2}{L_1 L_2 C_2} x + \frac{Z_1}{L_1 L_2 C_2} = 0 \tag{18}$$

It is known that all of these roots are negative, since all of the co-efficients of equation (**18**) are positive. We may, however,

substitute positive numerical values with the negative sign prefixed. Instead of equation (**17**), then, we may write

$$I = A_1 e^{-a_1 t} + A_2 e^{-a_2 t} + A_3 e^{-a_3 t} \qquad (\mathbf{19})$$

in which a_1, a_2 and a_3 will be positive.

For the ranges of values of the constants appearing in the coefficients of equation (**18**), it will contain a pair of complex imaginary roots. In this case, instead of a_1, a_2 and a_3, we may write a, $(b - jc)$ and $(b + jc)$, and for purposes of calculation, it will be convenient to write equation (**19**) in trigonometric form. Thus, instead of

$$I = A_1 e^{-at} + A_2 e^{-(b-jc)t} + A_3 e^{-(b+jc)t} \qquad (\mathbf{20})$$

we have

$$I = A e^{-at} + e^{-bt}\,(B \cos ct + C \sin ct) \qquad (\mathbf{21})$$

This equation represents a condition of damped oscillation superposed upon a condition of decay.

It is not easy to obtain the roots of equation (**18**) in terms of the constants involved in the equation, but the numerical values of the constants may be substituted for any particular case, and the solution obtained for the particular case. It is necessary, also, to determine the constants A_1, A_2 and A_3 or A, B and C. Having determined the constants A_1, A_2 and A_3; A, B and C may be determined independently, or from the relations

and
$$\left.\begin{aligned} A &= A_1 \\ B &= (A_2 + A_3) \\ C &= j\,(A_2 - A_3) \end{aligned}\right\} \qquad (\mathbf{22})$$

For determining these constants, since I_{L_2} and I_{C_1} are zero at the first instant, equations (**15**) and (**11**) give

$$\text{For } t = 0 \quad \left\{\begin{aligned} & I = -\frac{2E_1}{Z_1} \\ & \frac{dI}{dt} = 0 \\ & \text{and } \frac{d^2 I}{dt^2} = 0 \end{aligned}\right. \qquad (\mathbf{23})$$

Substituting these values in (**19**) and its derivatives, we obtain

$$A_1 + A_2 + A_3 = -\frac{2\,E_1}{Z_1} \tag{24}$$

$$a_1 A_1 + a_2 A_2 + a_3 A_3 = 0 \tag{25}$$

and

$$a_1^2 A_1 + a_2^2 A_2 + a_3^2 A_3 = 0 \tag{26}$$

whence

$$A_1 = \frac{a_2\, a_3}{(a_3 - a_1)\,(a_1 - a_2)}\,\frac{2\,E_1}{Z_1} \tag{27}$$

$$A_2 = \frac{a_1\, a_3}{(a_1 - a_2)\,(a_2 - a_3)}\,\frac{2\,E_1}{Z_1} \tag{28}$$

and

$$A_3 = \frac{a_1\, a_2}{(a_2 - a_3)\,(a_3 - a_1)}\,\frac{2\,E_1}{Z_1} \tag{29}$$

Substituting these values in equation (**19**) we have

$$I = \frac{2E_1}{Z_1}\left[\frac{a_2\, a_3}{(a_3 - a_1)\,(a_1 - a_2)}\,e^{-a_1 t} + \frac{a_1\, a_3}{(a_1 - a_2)\,(a_2 - a_3)}\,e^{-a_2 t} + \frac{a_1\, a_2}{(a_1 - a_3)\,(a_3 - a_1)}\,e^{-a_3 t}\right] \tag{30}$$

Now we wish to determine the voltages across the inductance L_1 and L_2. These are

$$E_{L_1} = L_1\,\frac{dI_{L_1}}{dt} \quad \text{and} \quad E_{L_2} = L_2\,\frac{dI_{L_2}}{dt} \tag{31}$$

For the latter, we obtain from equation (**15**)

$$\frac{dI_{L_2}}{dt} = \frac{dI}{dt} \tag{32}$$

whence, substituting the value of I from (**30**), we have

$$E_{L_2} = -2E_1 \frac{L_2}{Z_1}\left[\frac{a_1\, a_2\, a_3}{(a_3 - a_1)\,(a_1 - a_2)}\, e^{-a_1 t}\right.$$

$$\left. + \frac{a_1\, a_2\, a_3}{(a_1 - a_2)\,(a_2 - a_3)}\, e^{-a_2 t} + \frac{a_1\, a_2\, a_3}{(a_2 - a_3)\,(a_3 - a_1)}\, e^{-a_3 t}\right] \qquad (\mathbf{33})$$

We now obtain $L_1 \dfrac{dI_{L_1}}{dt}$ from equation (**13**).

Thus

$$L_1 \frac{dI_{L_1}}{dt} = L_1 \frac{d}{dt}\left(I_{L_2} + C_2 L_2 \frac{d^2 I_{L_2}}{dt^2}\right) \qquad (\mathbf{34})$$

Substituting the quantities in the parenthesis from equations (**15**) and (**30**), performing the required differentiations and simplifying, we have

$$E_{L_1} = -2E_1 \frac{L_1}{Z_1}\left[\frac{(1 + C_2\, L_2\, a_1^2)\, a_1\, a_2\, a_3}{(a_3 - a_1)\,(a_1 - a_2)}\, e^{-a_1 t}\right.$$

$$+ \frac{(1 + C_2\, L_2\, a_2^2)\, a_1\, a_2\, a_3}{(a_1 - a_2)\,(a_2 - a_3)}\, e^{-a_2 t}$$

$$\left. + \frac{(1 + C_2\, L_2\, a_3^2)\, a_1\, a_2\, a_3}{(a_2 - a_3)\,(a_3 - a_1)}\, e^{-a_3 t}\right] \qquad (\mathbf{35})$$

When the values of the constants in equation (**18**) are such as to give two complex imaginary roots, equations (**33**) and (**35**) are both transformed to the trigonometric form. The proper constants may be obtained directly from those of equations (**33**) and (**35**) by the relations given in (**22**). The roots a_2 and a_3 now being of the form $b - jc$, and $b + jc$, this gives

$$E_{L_2} = 2\, E_1 \frac{L_2}{Z_1} \frac{a(b^2 + c^2)}{c^2 + (a - b)^2}\left[e^{-at} - e^{-bt}\left(\cos ct - \frac{a-b}{c} \sin ct\right)\right] \qquad (\mathbf{36})$$

and

$$E_{L_1} = 2\,E_1 \frac{L_1}{Z_1} \frac{a(b^2 + c^2)}{c^2 + (a - b)^2} \Bigg\{ (1 + C_2\,L_2\,a^2)\,e^{-at}$$

$$- e^{-bt} \Bigg[\Big(1 + C_2\,L_2\,(2ab - b^2 - c^2) \Big) \cos ct$$

$$- \frac{a - b + C_2\,L_2 \{ b^2 (a - b) - c^2 (a + b) \}}{c} \sin ct \Bigg] \Bigg\} \qquad \textbf{(37)}$$

It has been found by Mr. J. E. Clem, who calculated the curves for this paper, that within the range where we apply the above equations the following simplifications are possible:

We have assumed L_1 and L_2 equal, and have therefore but one value of inductance as well as one of capacity. Dropping the subscripts, we have for equation (**18**)

$$x^3 + \frac{Z_1}{L} x^2 + \frac{2}{LC} x + \frac{Z_1}{L^2 C} = 0$$

Within the range of values used, $\frac{Z_1^2}{4L^2}$ is very small as compared with $\frac{2}{L\,C}$. The above equation may therefore, with sufficient accuracy, be written

$$x^3 + \frac{Z_1}{L} x^2 + \left(\frac{2}{LC} + \frac{Z_1^2}{4L^2} \right) x + \frac{Z_1}{L^2 C} = 0$$

This equation is factored, giving

$$\left(x + \frac{Z_1}{2L} \right) \left(x^2 + \frac{Z_1}{2L} x + \frac{2}{LC} \right) = 0$$

The first factor gives

$$x = - \frac{Z_1}{2L}$$

and the second

$$x = -\frac{Z_1}{4L} \pm \sqrt{\frac{Z_1^2}{16\,L^2} - \frac{2}{CL}}$$

But $\frac{Z_1^2}{16\,L^2}$ may be neglected whence

$$x = -\frac{Z_1}{4L} \pm j\sqrt{\frac{2}{CL}}$$

The oscillatory case applies, with

$$a = \frac{Z_1}{2L},\ b = \frac{Z_1}{4L},\ \text{and } c = \sqrt{\frac{2}{CL}}$$

Substituting these values in equations (**36**) and (**37**), and remembering that a^2 and b^2 are small, as compared with c^2, it is found that these equations are represented with sufficient accuracy by the following:

$$E_{L_2} = E_1\left[e^{-\frac{Z_1}{2L}t} - e^{-\frac{Z_1}{4L}t}\left(\cos\sqrt{\frac{2}{LC}}\,t - \frac{Z_1}{4\sqrt{\frac{2L}{C}}}\sin\sqrt{\frac{2}{LC}}\,t\right)\right] \quad \textbf{(36a)}$$

and

$$E_{L_1} = E_1\left[e^{-\frac{Z_1}{2L}t} - e^{-\frac{Z_1}{4L}t}\left(\cos\sqrt{\frac{2}{LC}}\,t - \frac{5\,Z_1}{4\sqrt{\frac{2L}{C}}}\sin\sqrt{\frac{2}{LC}}\,t\right)\right] \quad \textbf{(37a)}$$

Written in the general form, these equations are

$$E_{L_2} = E_1\left[e^{-at} - e^{-bt}\left(\cos ct - \frac{b}{c}\sin ct\right)\right] \quad \textbf{(36b)}$$

and

$$E_{L_1} = E_1\left[e^{-at} + e^{-bt}\left(\cos ct - \frac{5b}{c}\sin ct\right)\right] \quad \textbf{(37b)}$$

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 17, 1915.

HARMONICS IN TRANSFORMER MAGNETIZING CURRENTS

BY J. F. PETERS

ABSTRACT OF PAPER

The purpose of this paper is to show in a concise manner the cause and effects of higher harmonic currents in magnetizing currents of transformers.

A hypothetical case is analyzed to show the cause of the harmonics; then the schemes of connecting transformers that are commonly used for polyphase transformation are taken up, and the effects of the harmonics on each case pointed out.

The author also shows the reason why third harmonic voltages are not developed in the three-phase "core type" transformer when connected star-star.

IT IS well known that the higher harmonics in the magnetizing currents of transformers under certain conditions of operation produce badly distorted voltage waves. In general, the methods used to show the causes of these higher harmonics and the distortions which they produce have been rendered obscure by rather complex mathematics. The object of this paper is to present the problem in a more simple form without any complex mathematics so that the general principles involved may be understood with a minimum of effort on the part of the reader. Those points that require a special study are more thoroughly discussed in an appendix.

The permeability of sheet steel used in the construction of electrical apparatus changes as the magnetic flux density increases so that the rate of variation of the latter is less than that of the magnetizing current producing it. The induced voltage in the secondary and also the counter electromotive force in the primary of a transformer are proportional to the rate of change of the magnetic flux enclosing these windings. The rate of change of a sine function is a sine function 90 degrees later in time phase. Therefore, to produce a voltage having a sine wave, the rate of change in the magnetic flux also must be a sine wave.

On account of the change in permeability of the iron at

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different flux densities, the magnetizing current producing a sine wave of magnetic flux cannot itself be a sine wave. It has been found by analysis that the magnetizing current of a transformer producing a sine wave of voltage has a considerable third harmonic component. It also contains the higher odd harmonics (5th, 7th, 9th, etc.), but to a much less degree.

That the magnetizing current must contain a comparatively large third-harmonic component is shown by the following: A comparatively small current is required for the first part of the magnetic flux cycle, the density being low, while as the maximum flux density is approached a much larger current in proportion is required. Therefore, the current wave necessary to produce a sine wave of flux will be peaked. There will be

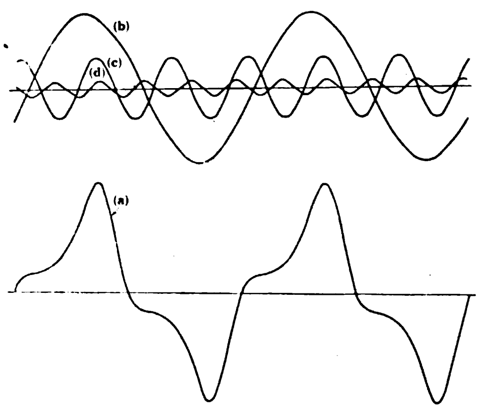


Fig. 1

only one peak per half cycle corresponding to the maximum flux density, and this peak must be made up largely of a harmonic that has but one maximum value, in the proper direction, per half cycle of the fundamental. The third harmonic has one and one-half cycles per half cycle of the fundamental and it is so located that its one maximum occurs a little later than the fundamental maximum. The other two maxima of the third suppress the fundamental in the first and last part of the half cycle. If some harmonic higher than the third had a considerable magnitude, the result would be that two maxima per half cycle would be produced in the magnetizing current. This could not produce a sine wave of voltage.

In Fig. 1, *a* represents the magnetizing current of a trans-

former. It is the resultant of a component at fundamental frequency *b*, a third harmonic component *c*, and a fifth harmonic component *d*. The magnitude of *c* is 40 per cent of the fundamental, and *d* is 10 per cent of the fundamental. The harmonics higher than the fifth were neglected for simplicity.

The magnetizing current of a transformer does not contain any even harmonics. This is obvious from the fact that the plus and minus half waves of a complete cycle of magnetizing current are the same. That is, it takes the same value of current to magnetize the core in one direction as it does in the other. Therefore, all the harmonics as well as the fundamental must at the beginning of the second half cycle be of the same value but in the direction opposite to that at the beginning of the first half. Only odd harmonics will satisfy this condition.

While the fundamental passes through ½ cycle, the third harmonic passes through 1½ cycles and the fifth harmonic

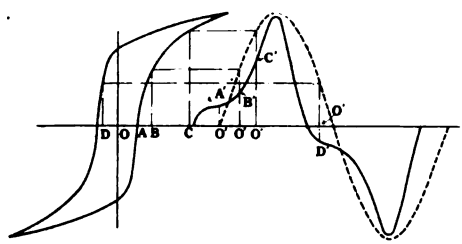


FIG. 2

through 2½ cycles, etc. All odd harmonics end with an odd number of ½ cycles and are therefore in the same relative position, but in the direction opposite to that at the beginning of the first half cycle. If the magnetizing current does not contain all of the harmonics necessary to produce a sine wave of voltage, then the voltage will contain those harmonics which the magnetizing current lacks, and possibly more. For example, when the magnetizing current does not contain the necessary third-harmonic component, the induced voltage contains a third-harmonic component.

A convenient means of showing the effect of changes in the shape of a magnetizing current wave is to plot the hysteresis loop and from this and the modified wave of magnetizing current construct the magnetic flux wave. The hysteresis loop corresponding to the magnetizing current wave shown in Fig. 1 (*a*), is plotted in Fig. 2. The abscissas *OA*, *OB*, *OC*, etc., in

the hysteresis loop equal the corresponding ordinates $O'A'$, $O'B'$, $O'C'$, in the magnetizing current wave. The wave shown in dotted line is the resultant magnetic flux wave. The method of construction is obvious from a brief scrutiny of this figure.

By following the same methods in Fig. 3, it is shown that when the magnetizing current is a sine wave, the magnetic flux is not a sine wave but is of the shape indicated by the dotted line. The magnetic flux wave for this figure was constructed from a sine wave magnetizing current and the hysteresis loop.

The analysis of this flux wave (See Appendix) gives a fundamental component of 17.62 sin (θ − 0.8 deg.), a third harmonic component of 3.9 sin (3θ − 5 deg.) and a fifth harmonic component of 2.2 sin (5θ − 24.3 deg.) where θ is the time angle in degrees and 0.8 deg., 5 deg. and 24.3 deg., are the angles at which the fundamental, third and fifth respectively lag behind

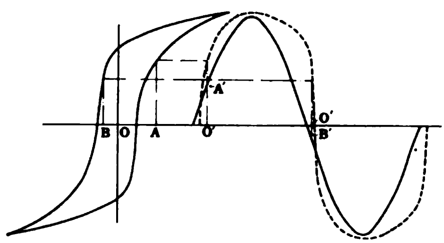


FIG. 3

the composite wave. This composite wave also contains odd harmonics higher than the fifth, but they are not taken into consideration here as previously stated.

The voltage produced by the magnetic flux shown in Fig. 3 is proportional to the rate of change, that is, the differential of the composite magnetic flux wave. The differential of this wave gives for the fundamental 17.62 cos (θ − 0.8 deg.), for the third harmonic component 11.7 cos (3θ − 5 deg.), and for the fifth harmonic 11 cos (5θ − 24.3 deg.). It will be noted that the third-harmonic component of voltage for the above case with a sine wave of exciting current is 65 per cent as great as the fundamental and that the fifth-harmonic component of voltage is 62.5 per cent as great as the fundamental.

In practically all schemes of connecting transformers for transmission purposes, the proper composite exciting current is supplied in which case large higher harmonic voltages are not

developed in the windings. In a comparatively few cases, however, it is not possible to draw the proper magnetizing current and consequently in these cases the higher harmonic voltages do exist. An effort will be made in the following to show how the magnetizing currents are supplied for the different schemes of connections and types of transformers and where harmonic voltages will appear.

The most frequent scheme of connecting transformers is three single-phase units connected into a three-phase bank is delta on the low-voltage side and in star on the high-voltage side. Assume that a bank so connected is used to step-down the voltage, and that the magnetizing currents for each of the three

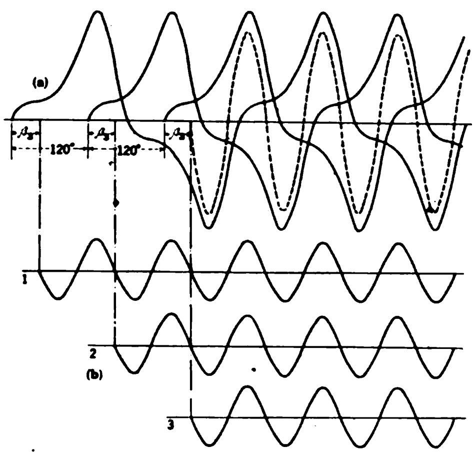


FIG. 4

units are as indicated by Fig. 1 (a). The magnetizing currents then for each phase contain, in addition to the fundamental, a third and a fifth-harmonic component. Since the transformers are connected in three-phase relationship their voltages are 120 degrees apart and, therefore, their magnetizing currents are 120 degrees apart. The magnetizing currents for the three units are shown in their proper phase position in Fig. 4(a). The three leads feeding the bank carry the current both to and from the transformers and, therefore, the resultant of the current in the leads must at all times be zero. But the resultant of the magnetizing currents for all three units in this case is, as shown in the appendix to this paper, 1.2 sin $(3\theta - \beta_3)$, where β_3 is the angle at which the third harmonic component

lags behind the composite wave. This resultant is not zero; therefore it will be seen that not all of the magnetizing current for this connection can be supplied through the three leads. The resultant current is shown dotted in Fig. 4 (*a*) which is obtained by combining the three waves.

It will be noted that this resultant current is at triple the fundamental frequency and that its magnitude is three times as great as the third harmonic component of magnetizing current for each phase. If the other higher harmonics of the magnetizing current had been taken into account (7th, 9th, 11th, etc.) in the above analysis it would be found that they all would be drawn from the line except the third and odd multiples of the third (9th, 15th, etc.). Therefore, the necessary third-harmonic component and its multiples to produce a sine wave of voltage must be supplied in some other manner for this scheme of connections, since they cannot be drawn from the line.

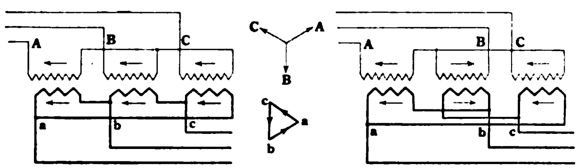


Fig. 5 Fig. 5A

In Fig. 4 (*b*) at 1, 2, and 3 are plotted the third harmonic components of the magnetizing currents for the three phases in their proper phase position with respect to the composite waves shown in the same figure at (*a*). It will be seen that these third-harmonic currents are all in the same direction at corresponding points. In Fig. 5, which is the star-delta scheme of connection, the arrows indicate the instantaneous directions in which the third harmonic currents should flow in the primary or star side. Since the third harmonic currents of all three phases are in phase with each other they have no return path in a star-connected circuit, therefore they cannot flow. Consequently third-harmonic voltages will be generated due to the absence of the third-harmonic currents. These voltages are all in the same direction since their components of the magnetizing currents are all in the same direction.

The generated or induced third-harmonic voltages appear in both the primary and secondary windings, but the delta-

connected secondary forms a closed local circuit for its third-harmonic voltage. Consequently, a third-harmonic current will circulate around this circuit and produce a third-harmonic magnetic flux which will cut both the primary and secondary windings. This flux will generate in both windings a counter third-harmonic voltage approximately equal and opposite to the one caused by the absence of the third-harmonic current in the primary. This results in cancelling all of the third-harmonic voltages, except that due to the reactance of the transformer which is generally so small that it is of no consequence.

It is evident from the foregoing that the third-harmonic component of the magnetizing current for a bank of transformers connected star-delta is supplied by a circulating current in the closed delta. If the units forming the bank require different values of third-harmonic currents, then, since the circulating current is the same in all three phases, one or two phases will be over supplied with this component of current while the other

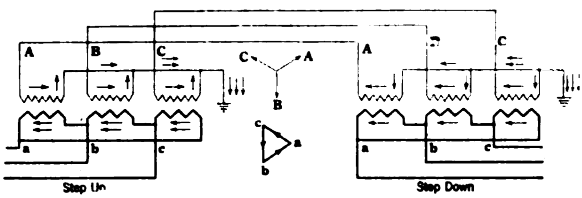


FIG. 6

phases will be under supplied. This will result in inducing a third-harmonic voltage of small value in all three phases.

It would be found by a similar analysis that the 9th and 15th harmonic currents and all odd multiples of the third are supplied by a circulating current in the secondary, while all other odd harmonic currents are drawn from the line. The magnitude of this circulating current is such that when it is multiplied by the secondary turns the product is equal to that of the required harmonic current in the primary multiplied by the primary turns. That is, the magnetomotive force is the same whether supplied by the primary or by the secondary, therefore the star delta connection relieves the primary of a part of the magnetizing current and adds it to the secondary.

If this bank be fed by another bank of transformers connected in star on the secondary side with its neutral grounded, then grounding the neutral of the step-down transformer bank, as shown in Fig. 6, produces closed circuits in the star-con-

nected side through which the third harmonic component of the magnetizing current can flow. These circuits for each phase consist of one line, the windings in each bank connected to this line, and the earth. The third-harmonic current carried by the ground connection is the sum of the third-harmonic currents in the three star-connected phases. With this connection a part of the third-harmonic component of the magnetizing current will circulate around the closed circuit in the delta connected secondary and a part will be drawn from the line using the earth as a return. The division of current between these two circuits depends upon their relative impedances. The difference in the magnitude of the third-harmonic currents required for the different phases of the bank, so connected, will be supplied through the grounded neutral. If the neutral of the secondary of the step-up transformer bank is not grounded then grounding the neutral of the step-down bank

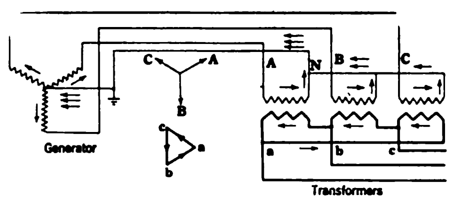


Fig. 7

will have no effect on the distribution of the third-harmonic component of the magnetizing current.

If a star-delta bank of transformers is fed directly by a star-connected generator and the neutral of generator and bank of transformers are connected together as shown by Fig. 7, then if the generator contains a third-harmonic voltage, this voltage will cause an additional third-harmonic current to circulate in the transformer and generator windings. The magnetizing current for this scheme of connections will be supplied in the same manner as when the source of supply is a bank of transformers with their secondaries connected in star, with its neutral grounded, as well as the neutral of the step-down bank, but the third-harmonic voltages of the generator are impressed on the transformers between line terminals and neutral.

The third harmonic voltages from the different phases of the generator are all in the same direction since the generator

voltages of fundamental frequency are 120 degrees apart and therefore, the third-harmonic voltages 3×120 or 360 degrees apart. These voltages are impressed on the primaries of the transformers which in turn induce corresponding voltages in the secondaries. The secondaries being connected in delta, their windings and connections between phases produce a closed local circuit for the induced third-harmonic voltages, consequently a third-harmonic current will circulate. The magnitude of this circulating third-harmonic current is determined by the total third-harmonic voltages of the generator and the combined impedance of the transformer bank and generator.

This current may be of considerable magnitude, for example: Assume that the normal output of the bank of transformers is small as compared with that of the generator, which is often the case when one generator feeds a number of independent lines, each having its own transformer bank. In such cases the generator impedance may be negligible when compared with that of one bank of transformers. Assume further that the generator has 10 per cent inherent third-harmonic voltage in each phase and that each transformer in the bank has 4 per cent inherent impedance at fundamental frequency, then at triple frequency the total impedance per phase will be approximately 3×4, or 12 per cent; consequently, a third-harmonic current of $10/12 = 83$ per cent of the normal transformer full load current will circulate in the primary and secondary of each transformer in the bank. The paths for these circulating currents on the generator side are over the line between generator and transformer terminals, through the transformer primaries, and back to the generator through the neutral connections. The current carried by the neutral connection will be the sum of the three currents in the phases. On the secondary or delta side of the transformer bank, the third-harmonic current will circulate around the circuit produced by the transformer windings and the connections between phases.

If the bank of transformers had been connected delta-delta, the magnetizing currents would have been supplied in a similar manner, except that a part of the third harmonic current would circulate in the primary local circuit and a part in the secondary, dividing up in inverse proportion to the impedance of the two windings. If the bank had been connected delta-star, all of the third-harmonic magnetizing current would have circulated in the primary local circuit.

With the bank connected star-star as shown by Fig. 8, the third harmonic component cannot flow, since it cannot be drawn from the line and there is no closed local circuit in which it can circulate. Consequently, a third-harmonic voltage will appear in both primary and secondary windings between the neutral points of the bank and the lines.

Since the third-harmonic component of magnetizing currents are in the same direction in all three phases, and the voltage produced by a magnetizing current is 90 degrees later in time phase, it follows that the third harmonic voltages are in the same direction in all three phases. The neutral point of the bank therefore, does not remain at zero potential but oscillates around the zero point at triple frequency. The voltages of the star-star connected bank are represented in Fig. 9 by means of the crank diagram. The three fundamental voltages are represented by the vectors A_1, B_1 and C_1, which are 120 degrees

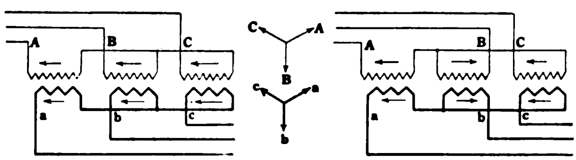


FIG 8 FIG 8A

apart. The neutral of the three-phase vector is located on the end of the third-harmonic voltage vector. There is only one third-harmonic vector, since the third-harmonic voltages of all three phases are in the same direction and, therefore, coincide. The voltage waves are constructed in the usual manner by rotating the radial vector in the direction indicated by the arrow, and projecting points out to corresponding points of time on the time angle axis, the third-harmonic vector, of course, being rotated three times as fast as the fundamental. The wave shown from 1 to 2 is that of the neutral point. From 2 to 3 are the composite waves of all three phases.

The voltage between lines, say A to B, Fig. 8 is the voltage from O to A, minus the voltage O to B, therefore, the voltage between lines A and B is the difference between wave A and wave B in Fig. 9. This voltage wave is shown dotted. It will be noted that this resultant is a sine wave and that it is 173 per cent of the fundamental in either phase OA or OB.

Therefore it is evident from the above that, although there are third-harmonic voltages in the phases of a star connected bank, they do not appear in the line. They do however produce extra stresses in the insulation of transformers.

If the primary neutral point of the bank is grounded and the secondary neutral of the step-up bank is not grounded, these third harmonic stresses will appear between coils and ground. Also, since the neutral point is pulsating or rotating around the zero point, it is obvious that the whole system is made to pulsate above and below ground an amount equal to the third-harmonic voltage in the phases. This may be of a dangerous value from the standpoint of charging current and also from the standpoint of static disturbances in neighboring communication lines. From the standpoint of charging current, let us assume that the third harmonic voltage is 50 per cent as great

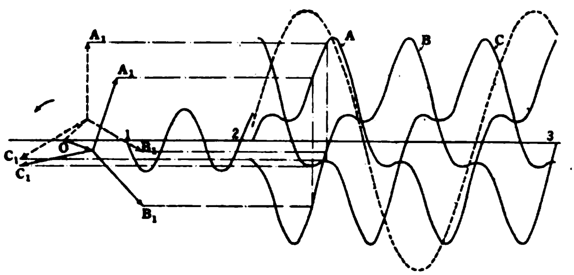


FIG. 9

as the phase voltage of fundamental frequency. Then, since it is at triple frequency the charging current due to it will be 3×50 or 150 per cent as great as that produced by the same voltage at fundamental frequency.

The third harmonic voltages in a star-star connected bank of transformers can be eliminated by providing a small winding in each phase and connecting these windings in delta. The third harmonic magnetizing current will then circulate in this winding in the same manner, and due to the same cause, as it does in the secondary of a star-delta connected bank. If the neutral point of the star-star connected step-down bank of transformers is grounded on the primary side, and the neutral of the step-up bank is grounded on the secondary side, as shown by Fig. 10, then there is a complete circuit through the lines and neutral connections for the third-harmonic com-

ponent of the magnetizing current and consequently the third-harmonic voltages will be eliminated from the transformers. This will of course eliminate electrostatic induction but the three triple frequency currents in phase in the lines and returning in the earth may cause electromagnetic disturbances in neighboring lines.

Transformers are sometimes connected in open delta or " V " for three-phase transformation. This scheme of connection is shown in Fig. 11 (a). The manner in which the third harmonic components of the magnetizing currents are supplied is very similar to that of the delta-connected bank. The phase voltages of fundamental frequency are 120 degrees apart, and therefore the third-harmonic components of the magnetizing currents are 3×120, or 360 degrees apart. That is, they flow in the same time phase as indicated by the arrows. With this connection, unlike the conditions with a closed delta, the third harmonic

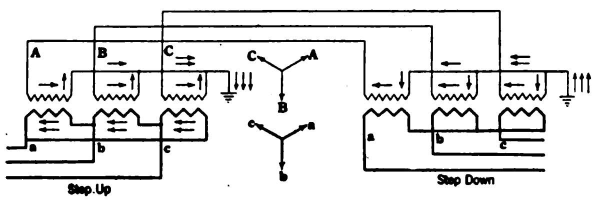


FIG. 10

component of the magnetizing current is drawn from the line through leads *A* and *C* and, therefore, must pass through the impedance of the line and generator or source of supply. Consequently there will not be quite sufficient third-harmonic current and a third harmonic voltage will exist in the phases. In most cases these third harmonic voltages are of small value and of little or no importance.

Fig. 11 (*b*) shows a three-phase—two-phase, connection magnetized from the three-phase side, and at 11 (*c*) is shown a three-phase *T*-connected bank. In both of these cases the magnetizing current for the transformers are 90 degrees apart in time phase, and therefore, the third-harmonic currents are 3×90 or 270 degrees apart. With these connections lead *A* carries the magnetizing current for one phase and *B* and *C* the magnetizing current for one phase plus one-half of the current from the other phase combined at 90 degrees; that is, $\sqrt{1 + 0.5^2} =$

113 per cent of the current for one phase. In these connections like the V, the third harmonic current flows through the impedance of the line. Therefore, a small third harmonic voltage may exist.

The foregoing considerations were based on the banks being made up of single phase units connected for polyphase transformation. If the three phase-banks consisted of three-phase units of the socalled " shell form," the conditions with respect to magnetizing currents and higher harmonic voltages would be substantially the same as for single-phase units connected in the same relation. In the three-phase shell form of construction, the magnetic circuits for the three phases are built up as one unit. The electrical connections for the middle phase are reversed as shown in Figs. 5 (a) and 8 (a), so as to place the magnetic flux of this phase 60 degrees from the fluxes of the phase on either side. The object of this reversal is to decrease the necessary area of the magnetic circuit between phases. Each phase of the unit has a magnetic circuit completely surrounding it and consequently there are no interchanges of magnetomotive forces from one phase to another. But if the three phase banks consist of three-phase units of the core " type " construction, the conditions with respect to magnetizing currents and higher harmonic voltages in the star-star-connected bank are considerably changed.

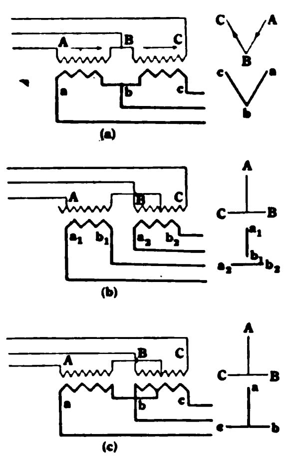
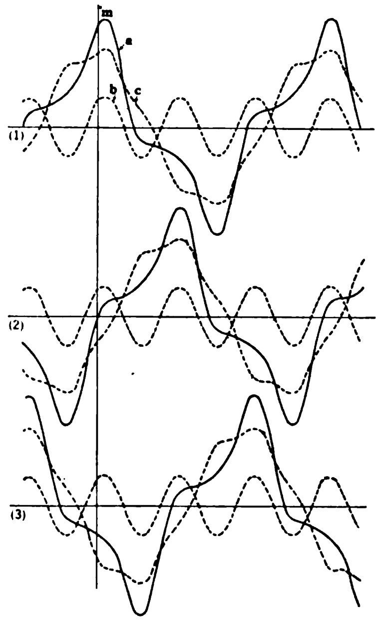


FIG. 11

With the latter type of construction the magnetic circuit for the three phases are mutually connected, in that the magnetic flux of any one phase has its return path through the other two phases. Now since the magnetic fluxes go and return through the same three cores it is evident that the resultant of the three fluxes in any one direction must at all times be zero. But, if there are any third harmonic voltages in the phases due to the absence of the third-harmonic magnetizing currents in the star-star-connected unit they are induced in the same direction in all three phases and, therefore, their third-harmonic magnetic fluxes are all in the same direction.

This would require that the third-harmonic flux return outside of the cores through high reluctance paths. They would consequently be of very small value.

It would appear from the above that third-harmonic voltages which are due to the absence of the third-harmonic component of magnetizing currents in the star-star-connection are prevented in the three phase core form units by the high reluctance return paths of the third harmonic magnetic fluxes. But this is not strictly true; what really happens is that the deficit in magnetomotive force in parts of the cycle in each phase is supplied by the other two phases. Fig. 1 shows three magnetomotive force waves 1, 2, and 3, 120 degrees apart. (*a*) is the required wave of magnetomotive force to produce a sine wave of magnetic flux. (*b*) is the third-harmonic compounent of the required magnetomotive force wave, and (*c*) is the magnetomotive force wave that is drawn from the line. It is wave (*a*) minus wave (*b*). Referring to point *m*, it will be seen that (*c*) in 1 is lacking sufficient magnetomotive force, while 2 and 3 at the same point have a surplus of magnetomotive force. Consider this point on the cycle to be such as to have a magnetic flux up through core *A* in Fig. 13, and down through *B* and *C*. The extra magnetomotive force tending to produce the surplus of flux down through *B* and *C* will be expended in supplying the deficit up through *A*, *A* being the return path for *B* and *C*. In this way there is an interchange of magnetomotive forces between phases, which results in the



Fif. 12

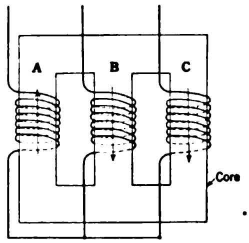


Fig. 13

production of sine wave of magnetic flux and, therefore sine wave of voltage in all three phases.

APPENDIX

In analyzing the magnetic flux wave of Fig. 3, the first half of the cycle was divided into 15 parts and the height of the y ordinates for the different parts were measured. These measured values together with the time angle and its sine and cosine values are given in Table I, II and III. Table I gives the data for the fundamental component, Table II for the third harmonic and Table III for the fifth harmonic component. The first column

TABLE I.

MAGNETIC WAVE ANALYSIS FOR FUNDAMENTAL COMPONENT

θ	y	Sin θ	Cos θ	y sin θ	y Cos θ
0.	0.	0.	1.0	000	0.00
12.	8.7	0.208	0.978	1.81	8.51
24.	11.7	0.407	0.914	4.76	10.70
36.	13.0	0.588	0.809	7.64	10.51
48.	13.9	0.743	0.669	10.20	9.30
60.	14.65	0.866	0.500	12.70	7.32
72.	14.9	0.951	0.309	14.18	4.60
84.	15.0	0.995	0.105	14.92	1.57
96.	14.9	0.995	−0.105	14.82	− 1.56
108.	14.65	0.951	−0.309	13.92	− 4.54
120.	14.2	0 866	−0.500	12.30	− 7.10
132.	13.8	0.743	−0.669	10.26	− 9.25
144.	13.	0.588	−0.809	7.65	− 10.50
156.	12.	0.407	−0.914	4.88	− 10.95
168	10.6	0.208	−0.978	2.20	− 10.36
180				7.5/132.24 17.62	− 1.75 ÷ 7.5 = −0.234

contains the time angles, the second column the y ordinates corresponding to the time angle in column 1. Column 3 contains the sine and column 4 the cosine of the time angles. Columns 5 and 6 are the products of the sines and cosines respectively of the time angle and the y ordinates. Columns 5 and 6 are added and their sums divided by $7\frac{1}{2}$. The quotients give the respective sine and cosine components of the separate harmonics.

From table I the fundamental wave is made up of 17.62 $\sin\theta - 0.234 \cos\theta = 17.62 \sin(\theta - 0.8 \text{ deg})$.

From table II the third harmonic component is made up of $3.88 \sin 3\theta - 0.343 \cos 3\theta = 3.9 \sin(3\theta - 5 \text{ deg.})$, also from table

III, the fifth harmonic is made up of $2 \sin 5\theta - 0.905 \cos = 5\theta$ $2.2 \sin (5\theta - 24.3 \text{ deg.})$

The resultant of the magnetizing currents of three phases

TABLE II.

MAGNETIC FLUX ANALYSIS FOR THIRD HARMONIC COMPONENT

θ	y	Sin 3θ	Cos 3θ	$y \sin 3\theta$	$y \cos 3\theta$
0.	0.	000	+1.000	0.00	000
12.	8.7	+0.588	+0.809	+ 5.10	+ 7.00
24.	11.7	+0.951	+0.309	+11.12	+ 3.61
36.	13.0	+0.951	−0.309	+12.40	− 4.02
48.	13.9	+0.588	−0.809	+ 8.19	−11.25
60.	14.65	0.000	−1.000	0.00	−14.65
72.	14.9	−0.588	−0.809	− 8.78	−12.02
84.	15.0	−0.951	−0.309	−14.30	− 4.65
96	14.9	−0.951	+0.309	−14.20	+ 4.60
108	14.65	−0.588	+0.809	− 8.60	+11.80
120	14.2	0.000	+1.000	0.00	+14.20
132	13.8	+0.588	+0.809	+ 8.10	+11.10
144	13.0	+0.951	+0.309	+12.38	+ 4.01
156	12.	+0.951	−0.309	+11.40	− 3.70
168	10.6	+0.588	−0.809	+ 6.23	− 8.60
				7.5/29.04	−2.57 ÷7.5 = −0.343
180				3.88	

TABLE III.

MAGNETIC FLUX ANALYSIS FOR FIFTH HARMONIC COMPONENT

θ	y	Sin 5θ	Cos 5θ	$y \sin 5\theta$	$y \cos 5\theta$
0	0.00	000	+1.00	0.00	000
12	8.7	+0.866	+0.50	+ 7.52	+ 4.35
24	11.7	+0.866	−0.50	+10.20	− 5.85
36	13.0	000	−1.00	000	−13.00
48	13.9	−0.866	−0.50	−12.05	− 6.95
60	14.65	−0.866	+0.50	−12.70	+ 7.37
72	14.9	000	+1.00	000	+14.90
84	15.0	+0.866	+0.50	+13.00	+ 7.50
96	14.9	+0.866	−0.50	+12.90	− 7.45
108	14.65	000	−1.00	000	−14.65
120	14.2	−0.866	−0.50	−12.30	− 7.10
132	13.8	−0.866	+0.50	−11.90	+ 5.90
144	13.0	000	+1.00	0000	+ 6.50
156	12.0	+0.866	+0.50	+11.22	+ 6.00
168	10.6	+0.866	−0.50	+ 9.18	− 5.30
				7.5/15.07	−6.78 ÷7.5 = −0.905
180				2.0	

120 degrees apart when the current of each phase is made up of $1 \sin (\theta - \beta_1) + 0.4 \sin (3\theta - \beta_3) + 0.1 \sin (5\theta - \beta_5)$ is as follows:

	Fundamental	Third harmonic	Fifth harmonic
Phase A,	$1 \sin(\theta - \beta_1)$	$+ 0.4 \sin(3\theta - \beta_3)$	$+ 0.1 \sin(5\theta - \beta_5)$.
Phase B,	$1 \sin(\theta - \beta_1 + 120)$	$+ 0.4 \sin(3\theta - \beta_3 + 360)$	$+ 0.1 \sin(5\theta - \beta_5 + 600)$
Phase C,	$1 \sin(\theta - \beta_1 + 240)$	$+ 0.4 \sin(3\theta - \beta_3 + 720)$	$+ 0.1 \sin(5\theta - \beta_5 + 1200)$

First adding the fundamental.

$$\sin(\theta - \beta_1) + \sin\{(\theta - \beta_1) + 120\} + \sin\{(\theta - \beta_1) + 240\} =$$
$$\sin(\theta - \beta_1) - \tfrac{1}{2}\sin(\theta - \beta_1) + 0.866 \cos(\theta - \beta_1) - \tfrac{1}{2}\sin(\theta - \beta_1) -$$
$$0.866 \cos(\theta - \beta_1) = 0$$

Adding the third harmonic components.

$$0.4 \sin(3\theta - \beta_3) + 0.4 \sin\{(3\theta - \beta_3) + 360\} + 0.4 \sin\{(3\theta - \beta_3) + 720\} =$$
$$0.4 \sin(3\theta - \beta_3) + 0.4 \sin(3\theta - \beta_3) + 0.4 \sin(3\theta - \beta_3) = 1.2 \sin(3\theta - \beta_3)$$

Adding the fifth harmonic components.

$$0.1 \sin(5\theta - \beta_5) + 0.1 \sin\{(5\theta - \beta_5) + 600\} + 0.1 \sin\{(5\theta - \beta_5) + 1200\} =$$
$$0.1 \sin(5\theta - \beta_5) - 0.05 \sin(5\theta - \beta_5) - 0.0866 \cos(5\theta - \beta_5 - 0.05 \sin(5\theta - \beta_5) +$$
$$0.0866 \cos(5\theta - \beta_5) = 0.$$

Therefore, the resultant for the three phases equals 1.2 $(3\theta - \beta_3)$.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 17, 1915.

PHENOMENA ACCOMPANYING TRANSMISSION WITH SOME TYPES OF STAR TRANSFORMER CONNECTIONS

BY L. N. ROBINSON

ABSTRACT OF PAPER

The purpose of this paper is to demonstrate the phenomena attending the operation of star-star transformers with grounded neutral on the line side. Contrary to current opinions, the author believes the abnormal voltages and destructive effects, which often accompany star-star operation, are due to even harmonics, at least in a large number of cases. At high magnetic densities, the third harmonic voltage may be appreciable, but the indications are that the even harmonics will cause damage at nominal magnetic densities lower than those which require appreciable third harmonic exciting current.

The data on which the conclusions are based, include approximately 150 oscillogram waves and a correspondingly large number of meter readings. The data are omitted from the text to a large extent, because the details could not add materially to the discussion. The tests are simple and can easily to made with an oscillograph in any laboratory or substation. One precaution must be kept in mind, namely that the observations should start at low voltages, which may be increased gradually until the various phenomena are observed. Unless this is done, the equipment may be wrecked.

INTRODUCTION

HERETOFORE, the third harmonic voltage, required to produce the necessary third harmonic exciting current, has generally been charged with the destructive effects accompanying the operation of star-star transformer banks. This is a just accusation if it can be shown that the third harmonic voltage is large. The star connection is generally used in transmission work so that the neutral on the line side may be grounded. If the line side neutral is not grounded, there may be abnormal and dangerous leg voltages due to the third harmonic, as has been proved in specific cases; though wreckage is less common with this type of connection, as shown by European practise. But, when the neutral on the generator side of the bank is isolated and the line side neutral is grounded, the Y-capacitive susceptance of the line is in series with the inductive Y-exciting-susceptance of the transformer legs; the former susceptance is larger than the latter in a system involving a long transmission line;

hence, the equivalent reactance of the circuit for Y-currents is inductive and the third harmonic current lags, contrary to some recently accepted opinions. From this, it is seen that the impedance to Y-currents is not as large as might be supposed from a casual survey. Therefore, it is believed that the opinion that the third harmonic voltages are responsible for the destructive effects accompanying star-star operation with grounded neutral on the line side only, is based on the coincidence that the path for third harmonic current was apparently of high impedance in cases where destructive effects resulted from the use of the connection. So far as can be ascertained from published data, no oscillograms (or similar observations) nor records have been made of the forces at play when transformers or line insulators have been destroyed by abnormal phenomena due to star-star operation.

The author has observed even harmonics and badly unbalanced leg voltages in several different instances within a period of eight months. In all these instances, the paths for Y-currents were through the open circuit admittance of the transformer units. These observations were made under the following conditions:

1. A star-star bank, with generator side neutral isolated and line side neutral grounded. The duty was charging a line 37 miles long.

2. Another bank similarly connected, but composed of units made by a different manufacturer and of different ratings in every respect. The duty of this bank was the same as for that in case (1) but on another day.

3. A bank of 1:1 auto-transformer connected star with grounded neutral, at the sending end of the 37 mile line, which was charged by a delta-delta bank.

4. A bank of transformers stepping down from isolated neutral star to "interconnected" delta. In this instance, the current circulating in the "interconnected" delta contained prominent even harmonics.

5. A bank of 13,200:110-volt potential transformers connected star with grounded neutral to the sending end of the 37 mile line, which was supplied from a delta-star bank with isolated neutral. The secondaries of the potential transformers were open-circuited.

Data

Several phenomena appeared consistently, and they seemed to vary with the magnetic density in the transformers. However

the variation of impressed voltage and consequently the variation of the magnetic density were necessary in order to vary the Y-currents, which currents are believed to be directly responsible for the excessive leg voltages.

In some cases, when charging the line from transformers connected star-star with grounded neutral on the line side, an undertone of one-half fundamental frequency was present in the leg voltages, and in the currents on the generator side of the bank.

In some other cases, two of the leg voltages were approximately $\sqrt{7/3}$ times the delta voltage, while the magnitude of the voltage of the third leg was approximately normal, *i.e.* 58 per cent of the delta voltage. The leg voltages had distinctly different wave shapes, and their fundamental components were conspicuously not 120 degrees apart in time phase. The currents in the buses on the generator side of the bank were several times normal.

In still other cases, the leg voltages had double frequency components, approximately four times as large as the fundamental components, and the transformers vibrated internally.

In the case of the 1:1 auto-transformers, the delta voltages were almost double what they were when no Y-current could flow. The delta voltages were of fundamental frequency with no double frequency component, while the leg voltages contained the large double-frequency component.

In all cases in which the second harmonic was prominent in the leg voltages, it was in time phase in all three legs. This was proved by the oscillograms of the simultaneous values of the three waves, by a measurement of their vector sum, and by the fact that the second harmonic was not in the waves of delta voltages (voltages between line conductors).

Discussion

Case 1. The case in which the second undertone, or "one-half" harmonic was present, is explainable by a periodically reversing leg; *i.e.* one leg of the bank reversed once for each fundamental cycle, so that the fundamental current in the leg flowed in the same direction through the unit during the entire cycle. In the next cycle the leg reversed again, so that the fundamental current flowed in the opposite direction from that in the previous cycle.

It is to be noted that the voltage from one line conductor to

ground was approximately 58 per cent of the delta voltage, while the voltages to ground from the other two conductors varied from 58 per cent of delta voltage to 100 $\sqrt{7/3} = 153$ per cent of the delta voltage; *i.e.*, the voltages from these latter conductors to ground varied from normal to 264 per cent of normal Y-voltage. On a line with small factor of safety of insulation, this 164 per cent abnormal voltage might cause considerable damage.

The voltages between conductors (delta voltages) are normal if the bank is of star-star transformers with grounded neutral on the line side only, because the delta voltages on the station side are fixed by the generator, and the neutral on the station side of the bank is isolated and free to float.

Case II. In the case with the stable, unbalanced leg voltage condition, the neutral on the generator side of the bank assumed a fixed position with one leg reversed so that the voltages from two of the line conductors to ground were approximately $\sqrt{7} = 2.64$, times the voltage from the third conductor to ground.

A peculiar characteristic of this case was that different legs reversed at different times. The switching was done on the station side of the bank. The line was 37 miles of vertical type construction with no transpositions to balance the admittances to ground. Charging the line the first time, for example, leg No. 1 might reverse and continue reversed as long as the bank was excited. Switching off and on again might bring either leg No. 2 or leg No. 3 in reversed, and the reversed leg would be a stable condition as long as the transformers and line were energized. Occasionally, the three legs would come in without a reversed leg, and conditions would be normal.

Case III. At approximately 60 per cent of normal voltage impressed, the first star-star bank, which was observed, showed signs of distress by vibration noises. This condition followed charging the line and transformers through a three-pole oil-switch on the station side of the bank. The neutral on the station side was isolated and the line side neutral grounded. Investigation showed a second harmonic in the voltages from line conductors to ground. As stated above, this second harmonic was in time phase in all three legs and did not appear in the delta voltages, which latter were of normal magnitude. In this case, the second harmonic was approximately four times the fundamental component of the leg voltage.

In explanation: The impressed Y-voltage on the generator side of the bank produced an exciting current and corresponding flux, which induced the nominal line side leg voltage practically 180 times degrees behind the impressed leg voltage. The Y-susceptance of the 37-mile line is capacitive. The Y-currents in the line side of the bank must flow through the transformers with the station side of the bank open-circuited for Y-currents; *i.e.* the line side Y-reactances of the transformers are the open-circuit reactances. The capacitive Y-susceptance of the line is equivalent to a capacitive reactance, and is in series with the inductive Y-reactance of the transformers. The inductive reactance of the transformer is the larger of the two. Consequently, the resultant reactance of the circuit of Y-currents is inductive and less than the reactance corresponding to the exciting susceptance of the transformer. Hence, the line side Y-currents will be lagging, and of the order of magnitude required to excite the transformers at nominal voltage. The lag of this current will be more than 180 degrees and less than 270 degrees behind the impressed leg voltage on the generator side of the bank. The voltage induced by the flux corresponding to the Y-current is less than 90 time degrees ahead of the impressed leg voltage.

The "resultant" leg e.m.f. on the generator side of the bank is, therefore, the vector sum of the impressed leg voltage and the voltage induced by the Y-current. That is, the "resultant" leg voltages are above normal counter-e.m.f. and in three-phase relation. In order for this condition to exist, the neutral on the generator side of the bank must move in the e.m.f. diagram, and its motion is the effect of two sine wave e.m.fs. Thus, the equivalent motion of the neutral is in the axis perpendicular to the plane of the fundamental frequency e.m.fs. In other words, the e.m.f. vectors of fundamental frequency may be represented in the xy-plane, while the vector representing the motion of the neutral is coincident with the z-axis.

As to frequency, at the instant of the maximum value of the above "resultant" leg voltage, the neutral is at its maximum displacement. At the zero value of the "resultant" leg voltage, the displacement of the neutral is a minimum. At the minimum, or negative maximum of the "resultant" leg voltage, the displacement of the neutral is again a maximum, etc. Thus, it is seen that the displacement of the neutral is at double the frequency of the impressed leg voltage. Hence,

the counter e.m.f. between the actual neutral and the average position of the neutral is a double frequency e.m.f.

The above phenomena are transformed to the line side of the bank and the line side leg voltages are proportional to the square root of the sum of the square of the double frequency neutral e.m.f. plus the square of the vector sum of the impressed leg voltage and the fundamental voltage induced by the line side Y-current.

Because the neutral on the generator side of the bank is free to float in transformer banks connected as in this case, the delta voltages are not affected, but are transformed in the nominal ratio of the units.

As previously stated, the line side Y-current is more than 180 and less than 270 time degrees behind the impressed leg voltage. That is, the Y-current lags behind the line side "nominal leg voltage." In the general case then, the Y-current produces a component of flux opposite in phase to, and a component in quadrature to, the flux corresponding to the impressed leg voltage. The quadrature component of flux produces the mechanical stresses and vibrations evidenced by the noises.

Case IV. The 37-mile line was energized from a delta-delta bank of transformers. The neutral on the line side at the sending end was grounded by a star-connected bank of transformers whose secondaries were star-connected with no load, *i.e.*, open-circuited. Thus, the star transformers were three iron-clad reactances legged, one from each line conductor to ground. However, they presented the only path for Y-currents, and therefore operated as 1:1 auto-transformers in respect to Y-currents. The neutral of this bank, being grounded, could not pulsate to maintain the proper delta counter e.m.fs. The result was, that the delta voltage was raised to nearly twice the magnitude that existed when the line was disconnected; that is the path for Y-currents through the line and auto-transformers was essential to the phenomena; and the delta voltage was approximately $\sqrt{3}$ times the "resultant" leg voltage discussed in Case III. This excess delta voltage was dissipated in the line and backed up into the supply source, an extensive public service corporation network.

As expected, the second harmonic was prominent in the line Y-voltages, and not noticeable in the delta voltages.

Notwithstanding the excessive second harmonic leg voltages,

there was no appreciable third or sixth harmonic in the Y-voltages, though the Y-currents contained a large component of sixth harmonic frequency in both Case III and Case IV.

This fact proves that the Y-impedance of the line to third and sixth harmonic currents was small in this case, and it indicates that the same is true of other long lines.

Conclusions

The conclusions to be drawn from this demonstration are well known axioms so far as concerns commercial operation of star-star transformers or auto-transformers.

I. The use of star-star-connected transformers in long-distance transmission, with only the line side neutral grounded, is a dangerous practise unless a tertiary delta, or its equivalent, is used to stabilize the neutral.

II. The use of grounded neutral star-connected auto-transformers in long-distance transmission is also a dangerous practise unless a tertiary delta, or its equivalent, is used.

III. Grounding the neutral of an otherwise isolated transmission system by three iron-clad reactances or auto-transformers connected in star is a dangerous practise.

IV. The use of star-star transformers or auto-transformers on a grounded-neutral transmission system in safe if tertiary deltas, or their equivalents, are used at enough points to stabilize the neutral. With this type system, a liberal factor of safety is necessary in order to cover the emergency of the failure of the transformers containing the tertiary deltas.

V. The instability of the neutral due to double-frequency e.m.fs. is the reason why the grounded star transmission without secondary or tertiary deltas, or their equivalents, is condemned as bad practise.

VI. This demonstration leads to a comprehensive understanding of the possibilities and impossibilities, rather than the advantages and disadvantages, of the grounded star and isolated types of transmission.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 17, 1915.

DELTA-CROSS CONNECTIONS OF TRANSFORMERS
FOR PARALLEL OPERATION OF TWO- AND THREE-PHASE SYSTEMS

BY GEORGE P. ROUX

ABSTRACT OF PAPER

Two methods of transformer connections, the tee-cross and the delta-cross, are described with their application for parallel operation of two-phase and three-phase systems.

An attempt is made to explain as clearly as possible the voltage, current and phase relation, and the dephasing action which take place in each case.

The delta-cross system of connections lends itself to a great number of applications, either for the parallel operation of two-phase and three-phase systems or for the simultaneous supply of two-phase and three-phase power from one bank of transformers. It is to be noted that in this system of connections no special taps are required, except a 50 per cent tap on one transformer (usually easily obtainable), the compensation of one phase of the system being done externally by means of a small booster transformer.

The simplicity of connections, the feature that no special transformers are required, and no special taps necessary, give the electrical engineer facilities to meet promptly and economically the requirements inherent to two-phase and three-phase simultaneous distribution from only one transformer bank.

IN THE merger and consolidation of electric properties into larger systems, the electrical engineer, in his task of rehabilitation and reorganization of the physical properties for more convenient and economical operation, very often finds two generating plants that could be operated in parallel, but unfortunately, one has a two-phase and the other a three-phase generating equipment and distribution system.

The changing of either one of the systems to conform to the other involves considerable expense and a great deal of work and inconvenience, besides introducing some delay in completing the unification. It may also be desirable to supply the consolidated system from one plant and keep the other plant as a reserve or standby, at least for some time until the erecting of a central power plant is warranted.

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Under these conditions it is generally the practise to rewind the generators whenever this is feasible. This is quite an undertaking, usually interfering with the service, and is a useless expense if the rewound equipment is only temporary.

The parallel operation of two-phase and three-phase generators or of a two-phase and a three-phase system, or better yet the simultaneous distribution through four wires of two-phase and three-phase energy, can be effected in a very simple and economical manner, with no alteration or change in the mode of operation of the existing equipment, and at very little expense.

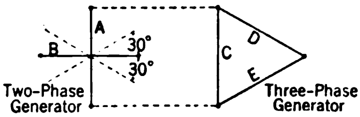

FIG. 1—ONE PHASE IN PARALLEL

PARALLELING TWO-PHASE AND THREE-PHASE GENERATORS

In this case we have two generators of the same voltage and frequency. Phase *A* of the two-phase generator is in phase with phase *C* of the three-phase generator, as shown in Fig. 1. These phases can therefore be connected to each other.

Phase *B* of the two-phase generator is 30 degrees from phases *D* and *E* of the three-phase generator, and it is necessary to swing this phase from 90 degrees of phase *A*, 30 degrees one way and 30 degrees the other, that is, make this phase oscillate to keep it in phase with the two other phases of the three-phase generator.

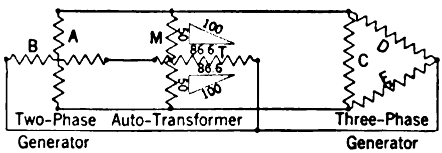

FIG. 2—PARALLELING TWO-PHASE AND THREE-PHASE THROUGH AUTO-TARNSFORMER

To perform this operation automatically, we interpose between the generators an auto-transformer consisting of two transformers, *M* and *T*, each having a single winding, and connect the systems as shown in Fig. 2.

Each transformer has a 100 per cent winding, the main transformer M, is provided with a 50 per cent tap, and the other, the teaser T, with an 86.6 per cent tap. They are not connected in T but in the form of a cross, with the 86.6 per cent tap of the teaser connected to the 50 per cent tap of the main.

The cross-connected auto-transformer will operate in the well known manner of the Scott connected transformer for phase conversion from two phase to three phase, and *vice versa*. The 13.4 per cent of the winding of the teaser operates as an auto booster to balance phase B, which otherwise would be short 13.4 per cent as only 86.6 per cent of its winding is utilized in phase conversion.

Fig. 3 shows the two generators connected on a four-wire busbar, to which single-phase, two-phase and three-phase feeders are connected and can be fed, with either machine operating singly or both in parallel.

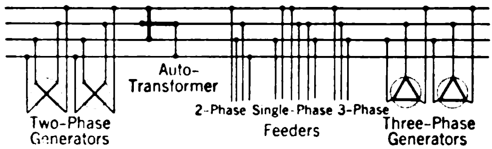

Fig. 3—Parallel Operation on Two-Phase and Three-Phase Generators on Four-Wire Distribution Bus, Through Auto-Transformer

It is obvious that all phases are equally balanced, no matter which machine operates, as in the case of a Scott connection. The two machines can be located in the same engine room, or in different power houses some distance apart, their number and size being immaterial, provided they have the necessary characteristics for their operation in parallel.

Quarter phase machines (that is, two phase-generators having their windings inter-connected) cannot be operated with this system, however, as the auto transformer would short circuit the phases.

Parallel Operation with High Tension System

For the parallel operation of a two-phase and a three-phase generating plant with a system of higher or lower potential, the two-phase and three-phase generators operating in parallel as in the above case, and at the same time in parallel with a sys-

tem of different potential, two other styles of connection can be used:

T—Cross connection. By the addition of a high-tension winding to the cross connected auto-transformers, as shown in Fig. 4, the three systems can be operated in perfect harmony and with a high degree of flexibility and independence. The diagram of Fig. 4 is also clear and simple enough, so requires no further explanation.

Delta—Cross Connection. Another system is still more convenient and advantageous. It consists of three transformers connected in closed delta, each transformer identical in size, windings and characteristics, and of a capacity corresponding to one-third of the requirements. No special taps need be provided except the usual 50 per cent taps to be brought out of one transformer only. The three transformers are connected in delta,

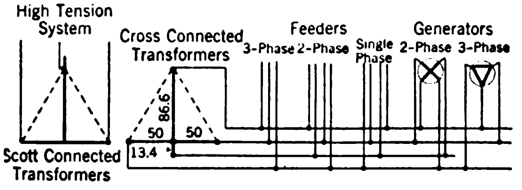

FIG. 4—PARALLEL OPERATION OF THREE-PHASE INCOMING OR OUT-GOING HIGH-TENSION LINE WITH TWO-PHASE AND THREE-PHASE GENERATORS ON FOUR-WIRE DISTRIBUTION BUS, THROUGH T-CROSS-CONNECTED TRANSFORMERS

as shown in Figs. 5 and 6, and a booster transformer having 13.4 per cent the capacity and voltage of one phase of the two-phase system, is connected to the 50 per cent tap of one of the transformers, completing the delta-cross connection.

The three delta-connected transformers, as per Fig. 6, behave like Scott-connected transformers through the 50 per cent tap of the main, and both phases AB and AC are swung alternately 30 deg. around; AD, the phase resultant of AB and AC is 90 deg. to phase BC, but with a value of only 86.6 per cent for AB. Adding outside of the delta DE, 13.4 per cent of phase AB, makes phase AE of the same value in both voltage and capacity as each of the others.

The 13.4 per cent addition (whose capacity is only 6.7 per cent that of the bank) is made to BC by using an ordinary pole type transformer connected so as to boost to the proper value.

Where potentials higher than 2300 volts are used in the two-phase system, a booster transformer with better insulation is naturally required.

Two-phase and three-phase current can be drawn from or put into the transformers connected in this style, and two-phase and

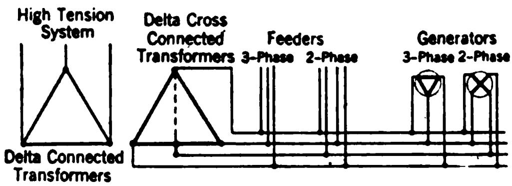

FIG. 5—PARALLEL OPERATION OF THREE-PHASE INCOMING OR OUTGOING HIGH-TENSION LINE WITH TWO-PHASE AND THREE-PHASE GENERATORS ON FOUR-WIRE DISTRIBUTION BUS, THROUGH DELTA-CROSS-CONNECTED TRANSFORMERS

three-phase generators both operated in parallel and with the high tension system, with absolute security and flexibility without affecting the operation of any part of the system.

Fig. 5 shows the practical operating conditions of such a system that has been in operation for four years with complete satisfaction, which consists of three 500-kv-a., 6600/2300-volt

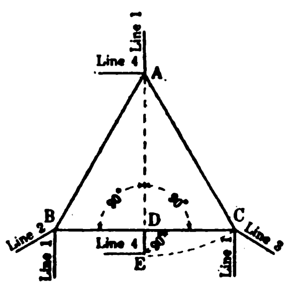

FIG. 6—DELTA-CROSS TRANSFORMER CONNECTION

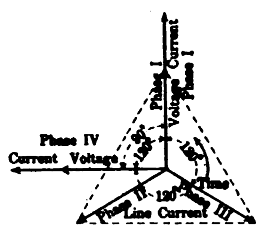

FIG. 7—PHASE, VOLTAGE AND CURRENT RELATIONS OF TWO- AND THREE-PHASE SYSTEMS

transformers connected delta-cross. Another installation with three 100-kw., 6600/2300-volt transformers connected delta-cross has been operating under similar conditions for three years, paralleling two generators two miles apart. The two-phase generator has been replaced lately by a three-phase machine of a larger capacity, and the two-phase apparatus on the

line has also been changed to three-phase. The three 100-kw. transformers have been kept in the plant and the only change made was the removal of the cross of the delta—that is, the small booster transformer, as there was no further use for the two-phase current.

Three two-phase systems each 120 deg. apart, and one three-phase system, could be supplied through this style of connection requiring only six wires, as illustrated in Fig. 6, with each phase 60 deg. apart; that is, a six phase system could be supplied and sub-divided again into six phases making a twelve phase system, each with a 30 deg. angle difference.

The removal of one of the two teaser transformers of Fig. 5—that is, operating in open delta—would not interfere with the two phase transformation, except that the capacity of the bank of transformers would be reduced correspondingly.

Should the two-phase system be abandoned later, the booster transformer can be removed and the bank operated closed delta in the ordinary way.

The diagrams of Figs. 6 and 7 show the principle of the transformation of three-phase to two-phase. The current of the teasers instead of coming to the middle of the main, enters the ends and leaves at the middle. A phase displacement of 30 deg. is effected or from 120 deg. to 90 deg. The phase so displaced, although having the proper angle, has not its original voltage value but only that of cosine of 30 deg. The complement is made through the booster transformer and is in phase with the phase boosted.

The three-phase currents are not displaced or affected in any way. It is evident that the current circulates in the windings and distributes itself automatically according to the resistance of the exterior circuits, that is of the two-phase and the three-phase system.

The applications of the systems of transformer connections described above, are practically unlimited, whether for permanent or temporary installations.

In the case of an isolated power plant supplying a two-phase system of distribution and later fed from a three-phase transmission line system, no changes are required to the existing local distribution system; and yet it can be gradually changed into a three-phase system, all new motor installations being three-phase. The motors of the old installations when replaced at any later time, can be changed to three-phase. The two-phase local generating plant can be operated any time without interfering in the least with the operation of the entire system.

A two-phase and a three-phase installation can be fed from one bank of transformers simultaneously, without mutual inconvenience. The 86.6 per cent tap on T- or Scott-connected transformers, can also be eliminated, as it is very often found difficult to provide for a tap of this value, which somewhat affects the internal stress of the transformer, while a 50 per cent tap is not objectionable. The eliminated complement of the 86.6 per cent tap can be compensated outside of the transformer, so that one transformer has a 100 per cent winding and the other 115.5 per cent thus restoring equilibrium in phase value.

The theory of the phase transformation which takes place in a system of transformers connected cross-delta, as shown in Fig. 6, is in a way similar to the dephasing action in T-connected transformers. The two-phase system is interlocked with the three-phase system, through one of their respective phases, which are in phase with each other. See Figs. 1 and 7.

Voltage Relation

Let us connect a three-phase system with a two-phase system of the same frequency and voltage, to three transformers having the same number of turns and the same impedance, and connected in closed delta as per Fig. 6, with a smaller transformer connected at D, midway between B and C; this transformer either to reduce or increase the terminal e.m.f. of line four so that the e.m.f. applied between D and A is only equal to $E\sqrt{3}/2 = 86.6$ per cent of the three-phase e.m.f. The resultant e.m.f. between B and A, and C and A, each 30 deg. from DA, will be $86.6/\cos 30$ deg. $= E$; that is, equal to and in phase with the three-phase e.m.f. between lines one and two, and one and three. Between lines two and three, the e.m.f. of the two-phase line is equal to and in phase with the e.m.f. of the third phase of the three-phase, both phases being in phase and interlocked.

Conversely, if we apply a three-phase voltage to the above transformers, the resultant voltage on the two phase side would be $E = 100$ between B and C, or at terminals of line one; and $E \times 0.866$ at A and D, or 86.6 to which the small transformer DE adds the complement of ($E - \cos 30$ deg.) $= 13.4$; the terminal voltage of line four will again be $86.6 + 13.4 = 100 = E$.

If we remove transformer two or one, we will have an open-delta three-phase connection and still have the same voltage and phase relations between the two systems.

The addition of the appendix, DE, forming the cross of the delta, serves no other purpose but that of balancing the voltage in one phase of the two-phase system, which can be but 86.6 per cent that of the three-phase system, the two systems acting as if the delta was superposed with a phantom inverted T-connection, of which 13.4 per cent of the upper end forms the appendix at the middle base of the delta, and acts only in combination with the short leg of the two-phase systems.

Current Relations

We have seen that one phase of the two-phase system is interlocked with at least one phase of the three-phase system. The voltage and current of these two phases are therefore in phase, the voltages having the same value, but the currents differing by a constant ratio throughout the cycle equal to $\sqrt{3}/2$.

The angular difference between each phase of the three-phase system is 120 deg. while only 90 deg. in the two-phase system. The respective angular position of each phase of both systems is shown in the crank diagram of Fig. 7. We therefore have phases I of each system in phase with each other, and phase IV of the two phase system 30 deg. in advance, or leading phase II, and 30 deg. behind or lagging, and in quadrature with phase III, time rotating counter-clockwise.

To have a better understanding of the dephasing operations which have to take place during one cycle or revolution, let us consider a three-phase system of 30-kw. and a two-phase system also of 30 kw., both connected to a circuit without inductance or capacity, each system to satisfy the following conditions: 30 kw. three-phase = $E\,I\,\sqrt{3}$ or 100 volts and 173.2 amperes per phase; 30 kw. two-phase = $EI + EI$ or 100 volts and 150 amperes per phase; that is, the current in each phase of the two-phase system differs $\sqrt{3}/2$ (or 0.866) with the current in each phase of the three-phase system, and is equivalent to

$$\frac{E\,I\,\sqrt{3}}{2\,E}$$

Connecting the primaries of three 10-kv-a. single-phase transformers in closed delta, as shown in Fig. 6, and omitting for the time being the secondary windings, these transformers can be considered as three auto-transformers with a ratio of 1 : 1.

These transformers are connected to the three-phase system, as indicated in Fig. 6, and in addition, we connect phase I of

the two phase system at B and C, and phase IV at A and D, where D is equidistant from BC.

Let us assume that only the two-phase generator is operated and that 30 kw. three-phase is required.

We will have the phase relations of the combined system, as shown by the polar co-ordinates of Fig. 8, from which we see that phase I of the two-phase system is parallel and therefore in phase and in time position with phase I of the three phase system.

Phase IV of the two-phase system is 90 deg. from phase I and exactly half way between phases II and III of the three-phase system; that is, leading phase II 30 deg. and lagging 30 deg. and in time quadrature phase III. In all the diagrams we assume the independent variable, the time, rotating counter-clockwise.

Taking the instantaneous values corresponding to time I, we have, as shown in Fig. 8, for the three-phase system.

Phase I, i cos 90 deg. at maximum and carrying 173.2 amperes.

Phase II, i cos 60 deg. and carrying 86.6 amperes.

Phase III, i cos. 60 deg. and carrying 86.6 amperes.

and for the two-phase system

Phase I, i cos 90 deg. at maximum and carrying 150 amperes.

Phase IV, i cos 0 and carrying no current.

Referring to Figs. 6 and 8, we see that the three-phase current flowing from O to T_1 is 173.2 amperes, and is made up from 150 flowing in phase I of the two-phase system from O through lines I, and passing into the transformers of Fig. 6 from B to C with two resultants at 30 deg. in BA and CA, each of $\dfrac{150}{2 \cos 30 \text{ deg.}}$ $= 86.6$ amperes in phases II and III toward O of Fig. 8, making again a total of $86.6 + 86.6 = 173.2$ from O to $T\,1$.

The current values and relations are also shown in crank diagram of Fig. 9, the dotted line showing the current in phase IV, which at that time is zero.

Taking another time position, as for $T4$, where the current in phase I of the two-phase and three-phase systems is zero, we have the following respective instantaneous values:

For the three-phase system

Phase I, i cos 0, carrying no current

Phase II, i cos 30 deg. carrying 150 amperes.

Phase III, i cos 30 deg. carrying 150 amperes.

and for the two-phase system

Phase I, $i \cos 0$, carrying no current.

Phase IV, i cos, 90 deg. carrying 150 amperes.

Following Figs. 6 and 10, we see that the current flowing through T 4 has the same value, 150 amperes in phase II and III, and at that time it is at maximum, or 150 amperes in phase IV, flowing toward O and entering the transformers at A, through line 4, where it divides into two halves, each 75 amperes 30 deg. apart, forming two resultants in A B and A C equal to $\dfrac{75}{\cos 30 \text{ deg.}}$ = 86.6 amperes, with a resultant of (86.6 + 86.6) cos 30 deg.

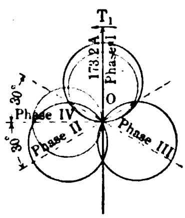

Fig. 8

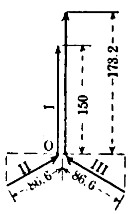

Fig. 9

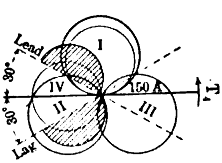

Fig. 10

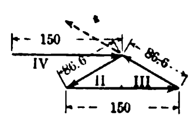

Fig. 11

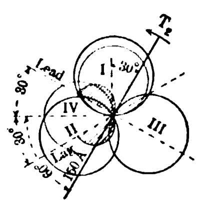

Fig. 12

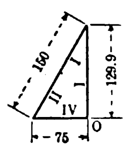

Fig. 13

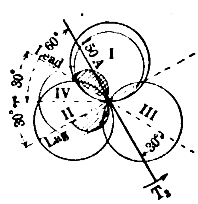

Fig. 14

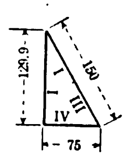

Fig. 15

Figs. 8–15—Polar and Crank Diagrams Showing Phase Relations and Current Values for T_1, T_2, T_3 and T_4

= 150 amperes in BC, flowing through T 4 of Fig. 10. The dephasing action is also shown in the crank diagram of Fig. 11. The current in phase I of the two-phase system at T 4 being zero, is shown in dotted line.

The splitting and phase relation of phase IV is best shown on Fig. 10, where the shaded portion indicates the position of each half of phase IV after being dephased, and where one-half is shown in time lag quadrature to phase III. The two halves are hinged at O in the polar diagram, or at A in the transformer connection, and open like a jaw 30 deg. each way as indicated.

If we now take time T 2, we have the following conditions—shown on Figure 12:

For the three-phase system

Phase I, $i \cos 30$ deg. carrying 150 amperes.

Phase II, $i \cos 30$ deg. carrying 150 amperes.

Phase III, $i \cos 0$ carrying no current.

and for the two-phase system

Phase I, $i \cos 30$ deg. carrying 129.9 amperes.

Phase IV, $i \cos 60$ deg. carrying 75 amperes.

At $T2$ we have different conditions in the two-phase system: 75 amperes in phase IV in series, and 90 deg. from 129.9 amperes in phase I. The resultant of these two currents is 150 amperes, as indicated in the crank diagram of Fig. 13, which flow in phase I and II of the three-phase system by T 2, current in phase III being at zero.

At T 3, we have the identical conditions that we had at T 2, except that the current is at zero in phase II, instead of in phase III, as shown in Figs. 14 and 15.

For any other time position during the cycle, the same dephasing process takes place automatically, with the same current relations and values corresponding to each angular position of the combined system.

The total power of each polyphase system is:
For the two-phase system,

$$\frac{EI\sqrt{3}}{2} + \frac{EI\sqrt{3}}{2} = \frac{EI\sqrt{3}}{2} = \frac{EI\sqrt{3}}{2}$$

and for the three-phase system,

$$\frac{E}{2}\, I \cos 30° + \frac{E}{2}\, I \cos 30° + E\,\frac{\sqrt{3}}{2}\, I = EI\sqrt{3}$$

Voltage and Phase Transformation

Adding a secondary winding of any given ratio of turns to the transformers of Fig. 6, and assuming that only half of the total 30-kv-a. of the bank is used in the feeders, requiring no voltage transformation, the other half or 15 kv-a. can be used at a higher voltage, the voltage transformation taking place in the ordinary way in the secondary windings of the transformers which can be connected either delta, open-delta or star, or any other convenient way. The system is necessarily reversible, and power of a higher voltage can be transformed to a lower voltage and dephased at will.

This system of transformer connection lends itself to a great number of combinations and answers practically all service requirements.

We might mention that it is possible to wind armatures of alternators with a cross-delta connection of Fig. 6, and supply two and three-phase currents from the same generator. This style of winding can also be applied to motors which would operate with two-phase or three-phase current at will, without alteration to the external winding connections.

In both cases the auxiliary winding necessary to complete the delta-cross, would be supplied outside of the machine, through a small transformer.

*To be presented at the Panama-Pacific Convention of
the American Institute of Electrical Engineers,
San Francisco, Cal., September 16, 1915.*

THE EFFECT OF TRANSIENT VOLTAGES ON DIELECTRICS

BY F. W. PEEK, JR.

ABSTRACT OF PAPER

In practise, failures of dielectrics are generally caused by transient voltages. It is, therefore, of great practical importance to determine the various phenomena affecting the strength of dielectrics and means of protecting them when they are subjected to known transient voltages. An impulse generator from which impulse voltages of any given wave front, length of tail, etc., can be obtained is described.

Energy is required to rupture gaseous, liquid and solid dielectrics; this introduces a time element. Thus, on account of this time lag, when voltage is applied at a very rapid rate, as by an impulse, spark-over does not occur when the continuously applied break-down voltage is reached. The voltage "over shoots" or rises above this value during the time rupture is taking place. This excess, or rise, in voltage above the continuously applied break-down value is greater the greater the rate of application. The time depends upon the nature of the dielectric, the dielectric field, the shape and spacing of the electrodes, initial ionization, etc.

The strength of air between spheres and needles for impulses of different front, length of tail, etc., is given, as well as the time in micro-seconds and the voltage required to rupture air between spheres and needles on the front of waves rising at various rates.

Transient spark-over and corona voltages for wires, surface spark-over, insulator spark-over, effects of polarity, air density, practical application, etc. are given.

Transient spark-over voltage and time are recorded for oil, and various solid dielectrics.

The general laws of breakdown of dielectrics by transient voltages are summarized.

INTRODUCTION.

ENERGY is required to break down gaseous, liquid and solid dielectrics. This introduces a time element. As an example consider air. For continuously applied a-c., or d-c. voltages, rupture occurs when a given gradient is reached. This voltage gradient is constant and is termed the strength of air.

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The author wishes to acknowledge indebtedness to Mr. B. L. Stemmons for his skilful assistance in making experiments and calculations.

See Hayden and Steinmetz—Disruptive Strength with Transient Voltages, TRANS. A. I. E. E., 1910.

It may be defined in terms of the electron theory as the gradient that is necessary to bring the ions up to sufficient velocity to produce other ions by collision with atoms or molecules. Breakdown takes place when ionic saturation is reached along a given path. The time element is not noticeable when the voltage is continuously applied. If, however, the time of application is very short, or limited, as is the case with transients, a higher voltage is required to produce ionic saturation in the limited time, than when the voltage is continuously applied.

The rupturing energy and the time to cause rupture when a

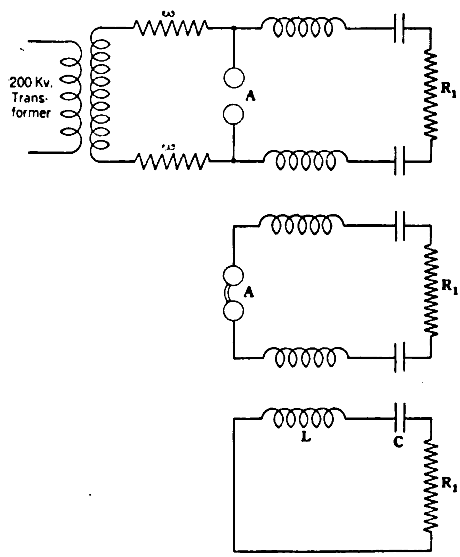


Fig. 1

given transient voltage is applied, vary with the dielectric material, the dielectric circuit, thickness of material, initial ionization, etc. Data on, and the law of the variation of, insulation strength when subjected to transient voltages is of great practical importance, as most insulation failures are due to such voltages.

The following investigation was made to determine the various phenomena affecting the strength of dielectrics when subjected to transient voltages. In order to make such an investigation a generator capable of supplying impulses of given wave front, tail, etc., is necessary.

Method of Producing Known Transient Voltages

The Impulse Generator. The impulse generator is shown in Fig. 1. Its operation is as follows: Constants of the circuit, C, L and R_1, are adjusted for the desired impulse, and the sphere gap A set for a given voltage, E. The transformer voltage is then gradually increased until the gap A discharges. Fig. 2 is an oscillogram of voltage across the gap A, and transformer current in the gap. This oscillogram shows that the gap at A breaks down at the maximum point of the 60 ~ wave, and that the voltage across A drops to zero. The arc at A holds and short circuits the transformer until the transformer voltage is removed. Gap A thus automatically measures the applied low frequency voltage and in effect, closes the circuit as a switch. This is the novelty of this generator and makes such tests possible. The transformer is separated from the impulse circuit by the resistance ω.

The equivalent circuit is shown in b or c, Fig. 1. As soon as the arc closes the circuit, the condenser discharges through the arc and through the inductance and resistance. The transient condenser discharge current causes a transient voltage across the resistance R_1. In the generator used in these tests, R_1 is a water tube resistance. L is made up of single layer coils in air. The condensers are made of glass coated with tinfoil. The foil is so placed that appreciable corona losses do not occur.

The discharge current of a condenser through a resistance and inductance is,[1]

$$i = \frac{E}{S}\left(\epsilon^{-\frac{R-St}{2L}} - \epsilon^{-\frac{R+St}{2L}}\right) \tag{1}$$

The transient voltage across R is

$$e = i\,R = \frac{ER}{S}\left(\epsilon^{-\frac{R-St}{2L}} - \epsilon^{-\frac{R+St}{2L}}\right) \tag{2}$$

Where E = voltage across gap A (or condenser at $t = 0$).
t = time in seconds.
L = inductance.
R = resistance of water tube, arc, coils, leads, etc.
R_1 = resistance of water tube which is practically

1. See Steinmetz, Transient Phenomena and Oscillations or Bedell and Crehore, Alternating Currents.

the total resistance of the circuit.

$$S = \sqrt{R^2 - \frac{4L}{C}}$$

If $R^2 < \frac{4L}{C}$

$$e = \frac{2ER}{q} E^{-\frac{Rt}{2L}} \sin \frac{q}{2L} t \qquad (3)$$

Where $$q = jS = \sqrt{\frac{4L}{C} - R^2}$$

Equations (2) and (3) are not changed as long as CL and CR are constant. They may be re-written, using

$$A = CL$$
$$B = CR$$

and thus involve only two constants of the circuit. With this substitution, (2) becomes

$$e = \frac{E}{\sqrt{1 - \frac{4A}{B^2}}} \left[\epsilon^{-\frac{B}{2A}\left(1 - \sqrt{1 - \frac{4A}{B^2}}\right)t} - \epsilon^{-\frac{B}{2A}\left(1 + \sqrt{1 - \frac{4A}{B^2}}\right)t} \right] \qquad (4)$$

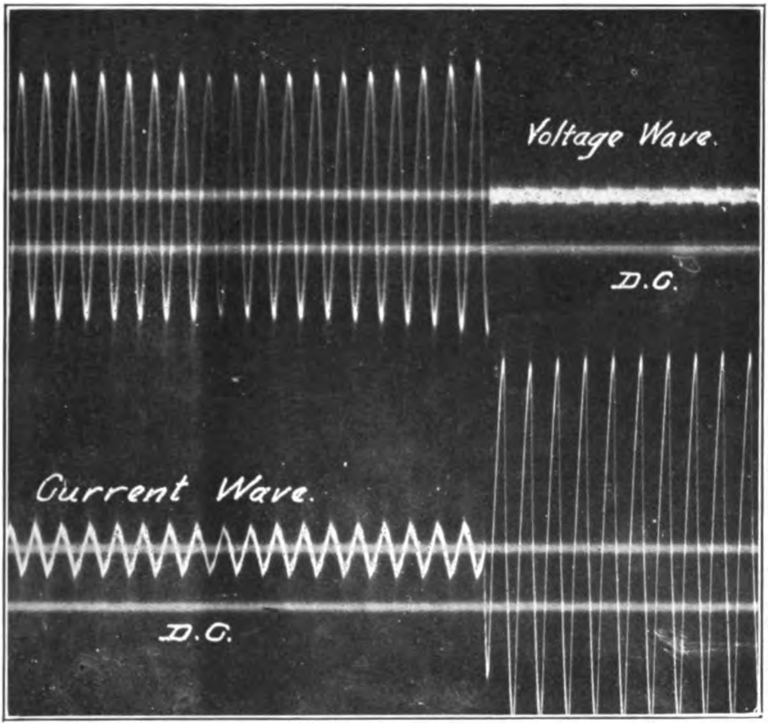
and (3) becomes

$$e = \frac{2E}{\sqrt{\frac{4A}{B^2} - 1}} \epsilon^{-\frac{B}{2A}t} \sin \left(\frac{B}{2A} \sqrt{\frac{4A}{B^2} - 1} \right) t \qquad (5)$$

(4) and (5) may be used in calculating the impulse voltage, e. For any given adjustment of A and B, the maximum of the impulse voltage, or the impulse voltage after any given interval of time, t, is [2]

$$e = KE \qquad (6)$$

2. If K is found by inserting t from (7) in (4) or (5), KE is the maximum impulse voltage.



[PEEK]

FIG. 2—VOLTAGE ACROSS GAP A—CURRENT IN TRANSFORMER

If the constants are such that $R^2 > \frac{4L}{C}$ the impulse is logarithmic and non-oscillatory and equation (4) is used. If the constants are such that $R^2 < \frac{4L}{C}$ the transient is oscillatory and the trigonometric equation (5) is used. By using (5) in such a way that only the first half wave is appreciable an impulse approaching a single half of a sine wave may be obtained. In such a case it is sufficient that the wave approximately follow a sine law from zero up to the maximum, and on the falling wave to a point below the 60 ~ breakdown voltage

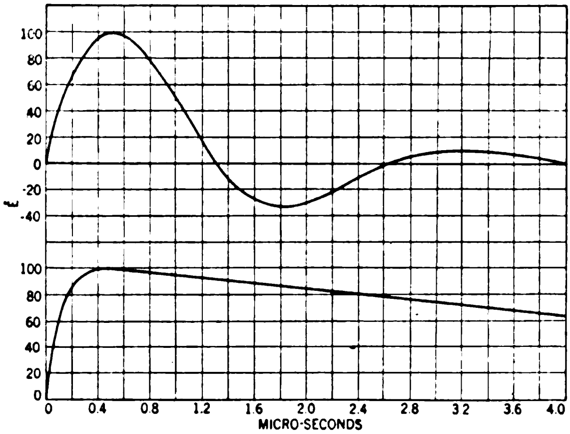


FIG. 3

of the insulation tested. Correction may be made for R_1 if necessary by multiplying e by $\frac{R_1}{R}$. The time at which the maximum of the wave occurs is

$$t = \frac{2L}{q} \text{ arc tan } \frac{q}{R} \tag{7a}$$

for the trigonometric case, and

$$t = \frac{L}{S} \log_e \frac{R+S}{R-S} \tag{7b}$$

for the logarithmic case.

Such waves are shown in Figs. 3 and 4. Tables I and II are given to show the method of making calculations.

The electrodes across which the transient spark-over voltages are to be studied, or the electrodes between which is placed the insulation under test, are connected across the resistance R_1. Gap A is set to give the desired impulse voltage. The transformer voltage is then increased until arc-over occurs. The test piece places a capacity, C_1, in multiple with the resistance, R_1. Unless C_1 is quite small compared with C the impulse will be modified by C_1. If not otherwise stated in the tests, C_1 is too small to affect results as shown by calculations and tests.

General Discussion of the Effect of Transient Voltages

A definite finite amount of energy is required to break down air or other insulation. This means that break-down cannot take place instantly upon the application of voltage but that finite

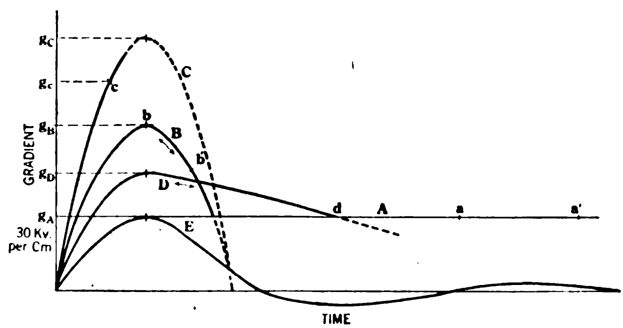


Fig. 4

time must elapse between the application of voltage and the break-down. The time depends upon the rate at which the voltage is applied, the dielectric material, the shape and spacing of the electrodes, initial conditions, etc. The strength of air under transient voltages will first be considered.

When the time of application of the voltage is not limited, as at 60 ~ a-c., or d-c., air breaks down at a gradient of 30 kv. per cm. maximum ($\delta = 1$). This may be again defined in terms of the electron theory as the gradient necessary to bring the ions up to sufficient velocity in their mean free path to produce other ions by collision with atoms and molecules. Break-down occurs when a sufficient number of collisions take place to produce ionic saturation.[3] Initial ionization, even to a considerable extent,

3. F. W. Peek, Jr.,—Law of Corona, I, II, III, A. I. E. E. Trans. 1911, 1912, 1913.

does not appreciably change this gradient for continuously applied voltages. However, the time required for ionic saturation to take place may be changed by initial ionization. This time

TABLE I.

CALCULATION OF IMPULSE WAVE

$C = 0.0005 \times 10^{-6}$ farads. $L = 0.312 \times 10^{-3}$ henrys. $R = 520$ ohms.

$$e_{max} = \frac{2ER}{q}\,\epsilon^{-\frac{R}{x}\arctan\frac{q}{R}}\sin\arctan\frac{q}{R} = 43.0$$

$$e = \frac{2E}{\sqrt{\frac{4A}{B^2}-1}}\,\epsilon^{-\frac{Bt}{2A}}\sin\frac{Bt}{2A}\sqrt{\frac{4A}{B^2}-1}$$

$A = CL = 15.6 \times 10^{-14}$ $B = CR = 2.6 \times 10^{-7}$

$\sqrt{\frac{4A}{B^2}-1} = 2.87$ $B/2A = 0.0834 \times 10^7$ $K = .43$

$$t = \frac{2L}{q}\arctan\frac{q}{R} = 0.5 \text{ micro-seconds} = 500 \text{ kc.}$$

t micro-secs.	$\frac{Bt}{2A}$	$\frac{Bt}{2A}\log_{10}\epsilon$	$\epsilon^{-\frac{Bt}{2A}}$	Radians $\frac{Bt\sqrt{\frac{4A}{B^2}-1}}{2A}$	Radians $\times 57.3$ = deg. θ	Sin θ	$\epsilon^{-\frac{Bt}{2A}}\sin\theta$	e kv.	% of e_{max} kv.
0.20	0.167	0.072	0.846	0.48	27.5	0.462	0.390	27.1	63.0
0.40	0.334	0.145	0.714	0.96	55.0	0.819	0.585	40.6	94.5
0.50	0.416	0.181	0.657	1.19	68.5	0.930	0.615	43.0	100.0
0.60	0.500	0.217	0.608	1.48	81.8	0.989	0.600	41.8	97.5
0.80	0.664	0.290	0.515	1.90	108.6	0.950	0.490	34.0	79.4
1.00	0.830	0.360	0.436	2.38	136.5	0.725	0.316	22.0	51.4
1.30	1.08	0.468	0.341	3.10	178.0	0.034	0.012	0.89	1.88
1.45	1.20	0.520	0.302	3.44	197.0	−.290	−.0875	−6.18	−14.2
1.60	1.34	0.581	0.258	3.82	219.0	−.630	−.162	−12.5	−26.1
1.80	1.49	0.646	0.226	4.28	245.0	−.906	−.205	−14.3	−33.3
2.00	1.67	0.725	0.189	4.78	274.0	−.994	−.187	−14.4	−30.3
2.25	1.87	0.814	0.154	5.36	308.0	−.788	−.121	−8.45	−19.7
2.50	2.09	0.905	0.124	6.00	344.0	−.276	−.034	−2.6	−5.5
3.00	2.50	1.080	0.078	7.17	412.0	+.788	+.061	4.28	+9.5
3.50	2.92	1.260	0.045	8.37	480.0	0.886	.038	3.0	6.3
4.00	3.34	1.450	0.035	9.58	550.0	−.173	−.006	0.46	0.99

Trignometric case Fig. 3.

element is not noticeable with continuously applied voltages. For instance, if a-c. voltages are continuously applied there is no indication whether break-down occurs at the first half cycle,

TABLE II.

CALCULATIONS OF IMPULSE WAVE

$C = 0.00133 \times 10^{-6}$ farads. $L = 0.604 \times 10^{-3}$ henrys. $R = 5270$ ohms.

$$e_{max} = \frac{ER}{S}\left\{ \frac{(R+S)}{(R-S)}^{-\frac{R-S}{2S}} - \frac{(R+S)}{(R-S)}^{-\frac{R+S}{2S}} \right\}$$

where $S = \sqrt{R^2 - \frac{4L}{C}} =$

$$e = \frac{E}{\sqrt{1 - \frac{4A}{B^2}}}\left(\epsilon^{-\frac{B}{2A}\left(1 - \sqrt{1 - \frac{4A}{B^2}}\right)t} - \epsilon^{-\frac{B}{2A}\left(1 + \sqrt{1 - \frac{4A}{B^2}}\right)t} \right)$$

$z = -\frac{B}{2A}\left(1 - \sqrt{1 - \frac{4A}{B^2}}\right)t$ $x = -\frac{B}{2A}\left(1 + \sqrt{1 - \frac{4A}{B^2}}\right)t$

$t = \frac{L}{S} \ln \frac{R+S}{R-S} = 0.5$ micro-second $= 500$ kc. $K = 0.95$

$A = CL = 8 \times 10^{-13}$ $B = CR = 7 \times 10^{-6}$

$\sqrt{1 - \frac{4A}{B^2}} = 0.968$ $\frac{B}{2A} = 4.37 \times 10^{-8}$

t micro-seconds	$\frac{Bt}{2A}\left(1 - \sqrt{1 - \frac{4A}{B^2}}\right)$	$z \log \epsilon$	ϵ^{-z}	$\frac{Bt}{2A}\left(1 + \sqrt{1 - \frac{4A}{B^2}}\right)$	$x \log \epsilon$	ϵ^{-x}	$\epsilon^{-z} - \epsilon^{-x}$	e kv.	% of e_{max} kv.
0.30	0.04	0.0173	0.963	2.58	1.13	0.074	0.889	91.8	96.5
0.50	0.07	0.0303	0.933	4.30	1.87	0.014	0.920	95.0	100.0
0.70	0.098	0.0425	0.908	6.00	..	..	0.908	93.8	98.8
1.00	0.14	0.0610	0.870	..	..	..	0.870	90.0	94.7
2.00	0.28	0.1210	0.758	..	..	..	0.758	79.5	83.5
3.00	0.32	0.1890	0.647	..	..	..	0.647	66.8	70.3
4.00	0.56	0.2430	0.572	..	..	..	0.572	59.2	62.3
5.00	0.70	0.3030	0.498	..	..	..	0.498	51.5	54.2
7.00	0.98	0.4250	0.378	..	..	..	0.378	38.5	40.5
10.00	1.40	0.6070	0.248	..	..	..	0.248	25.7	27.0
20.00	2.40	1.2100	0.061	..	..	..	0.061	6.3	6.6

Logarithmic case Fig. 3.

or after a number of half cycles have elapsed. In order to study the time element single impulses must be applied. When such impulses are of sufficiently short duration, higher voltages are required to produce ionic saturation in the limited time. If the number of available ions is small at the start, a longer time may be required to produce ionic saturation. Single impulses must not be confused with continuously applied high frequency. With continuously applied high frequency a greater number of half waves may be necessary to cause break-down than at 60 ∼ but a higher voltage is not necessary, as the effect of each half wave is cumulative. Note Fig. 4. If the voltage is such as to produce a gradient of 30 kv. per cm. and is continuously applied, as in wave A, break-down may take place at time a or a', etc., depending upon initial conditions, etc.; g_A is not changed, however.

If a single half cycle of a high frequency sine wave is applied so as *just to cause spark-over* it is found that the maximum voltage must be such as to produce a gradient g_B, while, break-down may take place at b or b'. Break-down takes place in shorter time than for A, but it is necessary to apply a higher average voltage during this limited time. If a very high transient over-voltage wave, C, is applied, break-down may take place at some point c, on the rising curve. The time is shorter than B, but the average voltage is much higher. If a wave D, with a long tail, and a maximum voltage just high enough to cause break-down is applied, rupture will probably take place at some point d, near the continuously applied wave A. The D voltage necessary just to cause arc-over is lower than B as the time is longer. In any case the insulation starts to break down as soon as the impulse voltage reaches the continuously applied break-down voltage. Thus, while the impulse voltage may not be sufficiently high to cause complete break-down, if it is higher than the continuously applied break-down voltage, it may do considerable damage to solid insulations. The wave E would not cause break-down in air; ionic saturation would not take place, but ionization would just begin.

This discussion applies particularly to non-uniform fields, (for instance, the field around needles), where the ions do not at the same time everywhere come up to sufficient velocity to produce others by collision. For more nearly uniform fields, as those around spheres, the time element is less.

From the above discussion it appears that:

1. Impulse voltages higher than continuously applied voltages are required to rupture insulation.

2. The increase over the continuously applied voltage depends upon the rate at which the voltage is applied or the steepness of the wave, and length of tail, time of application, initial conditions, etc.

3. The increase in voltage, or required time, depends upon the length of gap, and shape of electrode, or the nature of dielectric circuit. This is so, inasmuch as the rupturing energy, and therefore, the time, depend upon the amount of air that it is necessary to ionize in the path of the arc.

4. Dielectrics *begin* to rupture as soon as the impulse voltage reaches the continuously applied rupturing voltage; the effect is cumulative with successive impulses. A single impulse of short duration may cause complete break-down, if of sufficiently high voltage.

5. Needle gaps are affected by the time element to a greater extent than sphere gaps, because they require a greater rupturing energy.

6. The time lag may be explained by the energy theory and, also, is in accordance with the electron theory.

We have termed the ratio of the impulse break-down voltage to the continuously applied break-down voltage the "impulse ratio." So far the discussion has been general; a more detailed and theoretical discussion will be given later. The discussion as given applies more particularly to air; with slight modifications it also applies to other insulations as will appear later.

It now remains to test the above reasoning by experiment.

EXPERIMENTAL DETERMINATION OF THE EFFECT OF TRANSIENT VOLTAGES ON AIR

Spark-over of Spheres and Needles

Impulses of the Same Front, but Different Duration. Spark-over voltages were measured between spheres and needles with wave shapes as shown in Fig. 5. The instantaneous voltages are plotted in per cent of maximum. The time is measured in micro-seconds. The fronts of the waves are all practically the same and equivalent to that of a 500 kilocycle sine wave. The duration or the length of tail is, however, quite different. Table III gives the impulse break-down voltage, and the 60 ∼ break-down (continuously applied) voltage corresponding to different gap settings. These tests were made by setting the *A* gap for a given impulse voltage,

TABLE III.
IMPULSE SPARK-OVER VOLTAGES OF NEEDLES and SPHERES.
(EFFECT OF WAVE SHAPE.)

Needle gap.				Sphere gap. (25 cm. spheres.)			
Spacing cm.	Continuously applied (60 ~) spark-over kv (max.)	Impulse* spark-over kv (max.)	Imp. ratio	Spacing cm.	Continuously applied (60 ~) spark-over kv. (max.)	Impulse* spark-over kv. (max.)	Imp. ratio
Wave No. 1 (Sine Shape.)							
2.30	26.5	36.5	1.34	1.15	35.5	35.5	1.00
3.50	38.0	60.0	1.58	2.00	59.0	60.0	1.02
4.50	45.0	77.2	1.71	2.60	75.0	77.2	1.03
5.10	49.1	91.0	1.86	3.00	87.0	90.0	1.05
5.40	51.2	102.0	1.99	..	..	..	..
6.10	56.2	113.0	2.00	..	..	..	..
6.70	59.0	119.0	2.02	..	..	..	..
$R =$ 520 ohms		$L = 0.312 \times 10^{-3}$ henrys		$C = 0.0005 \times 10^{-6}$ farads			$K = 0.43$
Wave No. 2.							
3.50	38.0	49.2	1.29	1.70	49.0	49.2	1.00
6.80	59.5	90.0	1.51	3.10	88	90.	1.02
8.90	70.5	118.0	1.67	4.40	121	118	.97
10.80	79.5	142.0	1.78	5.30	142	142	1.00
12.60	87.0	162.0	1.86	6.10	160	162	1.01
14.10	95.0	181.0	1.91	7.00	180	181	1.00
16.00	104.0	210.0	2.03	7.80	200	210	1.05
$R =$ 2080 ohms.		$L = 0.37 \times 10^{-3}$ henrys		$C = 0.001 \times 10^{-6}$ farad			$K = 0.85$
Wave No. 3.							
7.10	61.0	80	1.33	..	..	..	..
12.30	86.0	124	1.44	..	..	..	..
17.30	109.0	160	1.47	..	..	..	..
20.10	122.0	192	1.57	..	..	..	..
21.50	134.0	217	1.75	9.30	225	217	.97
$R =$ 5270 ohms.		$L = 0.604 \times 10^{-3}$ henrys		$C = 0.00133 \times 10^{-6}$ farads.			$K = 0.96$
Wave No. 4.							
8.80	70.5	81.5	1.16	2.60	80	81.5	1.02
12.50	87.5	105	1.20	3.50	103	105	1.02
21.00	127	145	1.14	5.40	145	145	1.00
23.80	141	163	1.16	6.50	159	163	1.02
26.40	152	180	1.18	..	..	..	..
30.5	171	207	1.21	..	..	..	..
$R =$ 6800		$L = 0.604 \times 10^{-3}$ henrys		$C = 0.004 \times 10^{-6}$ farads			$K = 0.98$

*Calculated from circuit constants and voltage E, across gap A. See equations **1** to **7** $e_{max} = Ek$. Where t is obtained from **7**. See Tables I and II.

and adjusting the spheres or needles (not in parallel) across E_1 until arc-over occurred. This was repeated for different voltages until a curve was obtained.

Looking at Fig. 5 wave No. 4 is of longest duration, while wave No. 1 is of shortest duration. Wave No. 1 may, in fact, be considered as equivalent to a single half cycle of a 500 kilo-cycle sine wave. The oscillation may be neglected, as its maximum value for any given spark-over is kept below the continuously applied spark-over voltage.

According to the general discussion above, a much greater spark-over voltage should be required, for a given spacing when wave No. 1 is used than with 60 ~, the spark-over voltage for

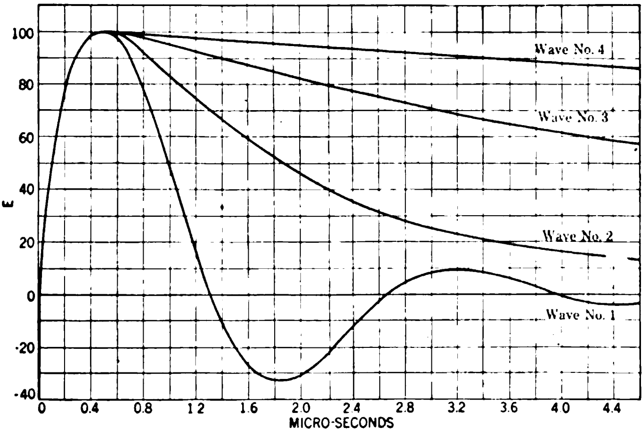


FIG. 5

wave No. 1 should also be greater than for waves Nos. 2, 3 and 4. The spark-over voltage of wave No. 4 should be lower than for waves Nos. 1, 2 and 3 but greater than 60 ~. This applies particularly to needles. With spheres at limited spacings, (not greater than the sphere diameter), where the field is more or less uniform, less effect due to limited time should be expected. In a uniform field the ions come up everywhere at the same time to sufficient velocity to produce others by collision. The path is of minimum length. Spark-over is the first evidence of stress. With needles considerable energy must be expended in corona in a large space before spark-over can occur. The length of the path is a maximum.

Such data on spheres and needles are tabulated in Table III

and plotted in Fig. 6. The experimental results check the general discussion. For example, looking at Fig. 6, at 10-cm. spacing the spark-over voltage of needles at 60 ~ is 75 kv.; with wave

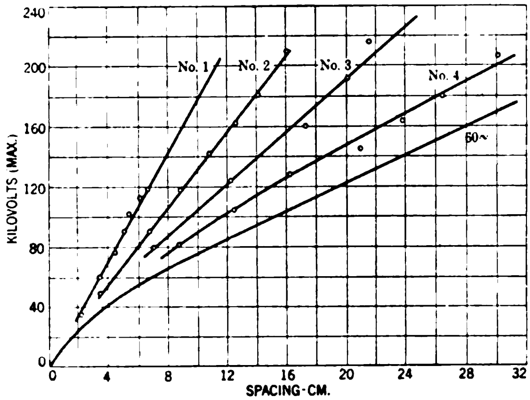


FIG. 6—IMPULSE SPARKOVER VOLTAGES OF NEEDLES EFFECT OF WAVE SHAPE

Numbers on curves refer to waves in Fig. 5.

No. 1 it is 188 kv.; with wave No. 2 it is 131 kv.; with wave No. 3 it is 104 kv.; with wave No. 4 it is 90 kv. The *total* time that waves Nos. 1, 2, 3 and 4 at the voltages just given are above the 60 ~ voltage is approximatly 0.95, 1.52, 2.70 and 5.0 micro-

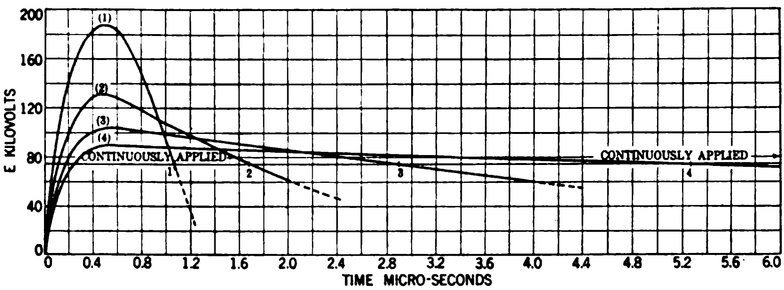


FIG. 7—CONTINUOUSLY APPLIED, AND VARIOUS IMPULSE VOLTAGES JUST TO CAUSE SPARKOVER—10-CM. GAP BETWEEN NEEDLES

[Note time of various impulses above continuously applied.]

seconds[4] respectively. See Fig. 7. Where the maximum of the impulse voltage is very little above the continuously applied voltage the time may be comparatively very great.

4. One millionth of a second.

The effect of these voltages on spheres is given in Table III and plotted in Fig. 8. The drawn curve is the 60 ∼ curve. The points are measured impulse values. It is seen that these fall close to the 60 ∼ curve where the sphere diameter is large compared to the spacing, or where the field is fairly uniform, as was the condition under which tests were made. It would thus appear that the sphere offers a fairly accurate means of measuring transient voltages of steep wave front. The applied impulse voltages measured by spheres (with the above limitations) check well with the voltages calculated by considering the transient current flowing through the resistance R_1. *Thus the time, or more exactly the energy, required to spark-over a sphere gap is much less than that required for a needle gap;* the amount of air that it is necessary to ionize before rupture is much less for the sphere. In all cases tests were made to show that the change in capacity of the gap and stand did not effect the impulse.

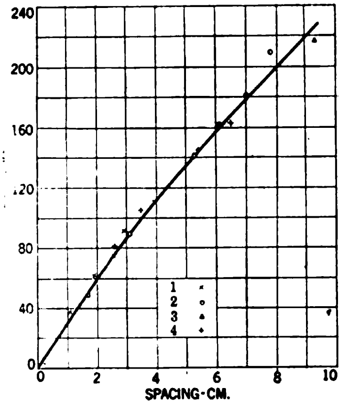


FIG. 8—IMPULSE SPARKOVER OF 25-CM. SPHERES—EFFECT OF WAVE SHAPE

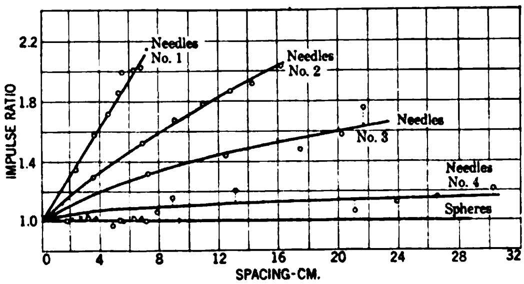


FIG. 9—IMPULSE RATIO OF NEEDLES AND 25-CM. SPHERES—EFFECT OF WAVE SHAPE

Wave No 1, Fig 5, × Wave No. 3, Fig. 5 △
" " 2 " " O " " 4 " " +

The impulse ratio for spheres and needles is shown in Fig. 9. It will be noted that it is practically unity for spheres; for needles it increases with the gap length and with decreasing time of application.

Variation of Spark-over Voltages of Spheres and Needles for Single Half-Cycle Sine Wave Impulses Corresponding to Different Frequencies

In Table IV spark-over data are given for spheres and needles for different single sine wave impulses. These impulses approximately correspond to single half cycles of sine waves of different frequencies.

TABLE IV.

VARIATION OF SPARK-OVER VOLTAGES OF SPHERES AND NEEDLES FOR SINGLE HALF CYCLES OF SINE WAVES CORRESPONDING TO DIFFERENT FREQUENCIES.

Needles				Spheres 25 cm.			
Spacing cm.	60 ~ spark-over kv.(max.)	*Impulse spark-over kv. (max.)	Impulse ratio	Spacing cm.	60 ~ spark-kv (max.)	Impulse* spark-over (max.)	Imp. ratio
			31 Kilocycles.				
5.20	51.0	51.0	1.00	1.70	51.0	51.0	1.00
9.00	71.5	71.5	1.00	2.40	71.5	71.5	1.00
12.10	86.0	87.2	1.01	3.00	86.0	87.2	1.01
15.00	99.0	101.0	1.01	3.60	102.0	101.0	.99
15.90	105.0	113.0	1.07	4.00	113.0	113.0	1.00
17.20	110.0	122.0	1.10	4.40	122.0	122.0	1.00
18.50	116.0	130.0	1.12	4.80	130.0	130.0	1.00
R = 2000 ohms		L = 16.1 × 10^{-3} henrys		C = 0.0024 × 10^{-6} farads.			K = 0.480
			55 Kilocycles				
3.50	38.0	38.0	1.00	1.25	38.0	38.0	1.00
5.10	49.4	49.4	1.00	1.65	49.4	49.4	1.00
7.00	59.2	59.2	1.00	2.00	59.2	59.2	1.00
8.50	69.0	69.0	1.00	2.35	69.0	69.0	1.00
9.60	75.0	76.0	1.01	2.60	76.0	76.0	1.00
10.60	79.0	84.0	1.06	2.90	83.5	84.0	1.00
11.30	83.0	91.0	1.09	3.10	90.5	91.0	1.00
12.50	88.5	97.0	1.10	3.40	97.5	97.0	1.00
13.70	94.5	106.0	1.12	3.70	104.0	106.0	1.02
R = 700 ohms		L = 3.17 × 10^{-3} henrys		C = 0.004 × 10^{-6} farads			K = 0 457
			83 Kilocycles.				
2.40	29.6	30.4	1.02	1.00	30.4	30.4	1.00
3.80	41.5	43.8	1.03	1.50	43.8	43.8	1.00
5.70	53.3	56.5	1.06	1.95	56.5	56.5	1.00
7.10	61.5	68.0	1.10	2.35	68.0	68.0	1.00
8.40	68.5	77.5	1.14	2.70	77.5	77.5	1.00
10.80	80.0	91.7	1.15	3.20	90.5	91.7	1.01
11.80	85.0	103.0	1.21	3.60	102.0	103.0	1.01
13.40	91.5	123.0	1.34	4.25	120.0	123.0	1.02
15.10	100.0	137.0	1.37	5.00	135.0	137.0	1.00
R = 910 ohms		L = 2.5 × 10^{-3} henrys		C = 0.0024 × 10^{-6} farads			K = 0.515

TABLE IV—*Continued*

Needles				Spheres 25 cm.			
Spacing cm.	60 ~ spark-over kv. (max.)	*Impulse kv. (max.)	Impulse ratio	Spacing cm.	60 ~ spark-over kv. (max.)	Impulse* spark-over (max.)	Imp. ratio
			100 Kilocycles.				
2.70	31.8	35.4	1.10	..	..	..	..
6.50	58.0	65.0	1.13	..	..	..	..
9.0	71.5	89.0	1.26	..	..	..	..
11.4	83.5	110.0	1.32	..	..	..	..
13.6	93.0	127.0	1.36	..	..	..	..
..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..
R = 2080 ohms		$L = 2.50 \times 10^{-3}$ henrys		$C = 0.001 \times 10^{-6}$ farads.			$K = 0.60$
			230 Kilocycles.				
1.75	21.1	25.0	1.18	..	..	..	..
2.70	31.0	37.6	1.21	..	..	..	..
3.80	40.8	50.1	1.23	..	..	..	..
4.95	48.5	62.5	1.29	..	..	..	..
6.20	56.5	75.5	1.34	..	..	..	..
7.25	62.5	88.0	1.14	..	..	..	..
8.50	69.0	100.0	1.45	..	..	..	..
R = 500 ohms.		$L = 0.799 \times 10^{-3}$ henrys		$C = 0.0008 \times 10^{-6}$ farads			$K = 0.356$
			350 Kilocycles		12.5 cm Spheres		
2.20	26.1	32.6	1.25	1.05	33.0	32.6	.99
3.20	35.2	50.2	1.42	1.65	49.4	50.2	1.02
4.30	44.4	67.0	1.51	2.30	65.6	67.0	1.02
5.85	55.0	83.5	1.52	2.90	81.0	83.5	1.03
7.00	61.2	100.0	1.63	3.45	95.0	100.0	1.05
8.60	69.5	117.0	1.68	4.25	113.0	117.0	1.05
9.85	76.0	134.0	1.76	..	..	..	..
R = 430 ohms.		$L = 0.312 \times 10^{-3}$ henrys		$C = 0.001 \times 10^{-6}$ farads.			$K = 0.470$
			900 Kilocycles.				
1.65	9.2	14.2	1.52	0.40	14.1	14.1	1.00
1.20	15.2	28.3	1.86	0.90	28.2	28.2	1.00
1.80	21.6	42.3	1.91	1.40	42.3	42.3	1.00
2.60	29.7	56.5	1.92	1.90	55.0	56.5	1.02
3.10	33.9	70.7	2.08	2.40	68.0	70.5	1.03
3.60	38.9	84.7	2.18	2.90	82.0	84.5	1.03
4.00	42.3	99.0	2.34	3.50	95.0	98.5	1.04
..	..	..	..	3.70	100.0	106.0	1.06
R = 400 ohms.		$L = 0.166 \times 10^{-3}$ henrys.		$C = 0.00025 \times 10^{-6}$ farads.			$K = 0.35$

*Calculated from circuit constants and voltage E, across gap A. See equations **1** to **7**. $e_{max} = EK$ where t is obtained from **7**. See Tables I and II. K is constant for any given wave. The impulse voltages are obtained by multiplying the 60 ~ voltage E, by K.

Needles. The time range is from continuously applied (60 ~) to 900 kc. Applying the same reasoning used above, where the duration of the impulse is decreased, higher spark-over voltages should be required for needles; thus, the higher the frequency (the shorter the time) that the single half wave corresponds to, the higher the voltage that should be required to cause spark-over. The data is plotted in Fig. 10. It must be remembered that " frequency " is not used in the ordinary sense; it indicates here the time required for the voltage to reach a maximum along a sine curve. For instance, the 500-kc. wave reaches its maximum in

$$\frac{1}{4 \times 500{,}000} = 0.5 \times 10^{-6} \text{ seconds} = 0.5 \text{ micro-seconds.}$$

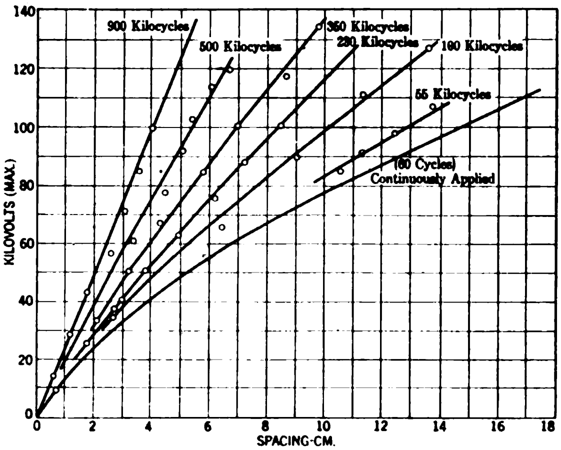


FIG. 10

Note the voltages corresponding to 5 cm. spacing. These voltages are 48 kv. for continuously applied, 57 kv. for 100 kilocycles; 64 kv. for 230 kilocycles; 75 kv. for 350 kilocycles; 93 kv. for 500 kilocycles and 123 kv. for 900 kilocycles.

The variation of voltage with frequency or 1/time in microseconds to reach the maximum is plotted for constant spacings in Fig. 11. These curves cut the axis (zero frequency) at the continuously applied spark-over voltage.

For any single half cycle sine-shaped impulse at any instant at a given " frequency " the rate of application of voltage across the gap, $\alpha = \frac{de}{dt}$. Average $\alpha = \frac{e_{max}}{t}$ is greater the higher

the maximum voltage. Thus, 15 500 kc. and 3-cm. spacing (Fig. 11), $e_{max} = 58$ kv.; $t = 0.5$ micro-seconds.

$$\alpha = \frac{58}{0.5} = 116 \text{ kv. per micro- sec.; at 5-cm. spacing}$$

$$\alpha = \frac{91}{0.5} = 182 \text{ kv. per micro-sec.}$$ The *law of spark-over of* needles for sine shaped impulses determined from data in Table IV may be expressed

$$e = 0.0176\, x f + e_0 \qquad (8)$$

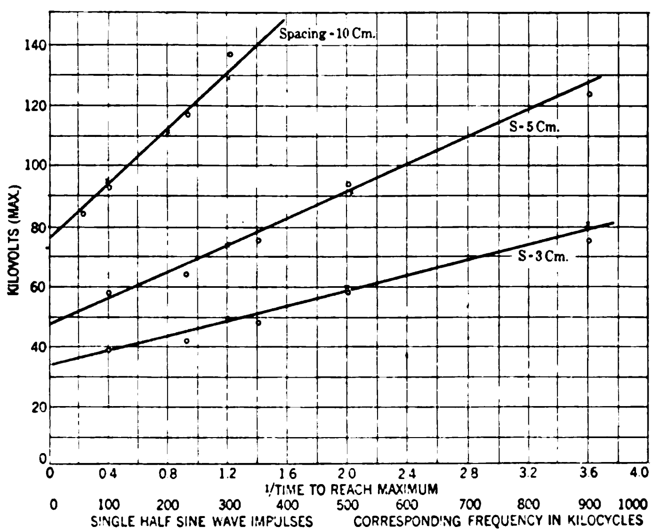


FIG. 11—IMPULSE SPARKOVER VOLTAGE OF NEEDLES—SINGLE HALF-CYCLE OF SINE WAVE OF DIFFERENT FREQUENCIES

where e = maximum of a sine shaped impulse just to cause spark-over.

e_0 = maximum 60 ~ spark-over voltage.

f = corresponding frequency of single half sine wave impulse in kilocycles.

x = spacing in cm.

e_1 = $0.0176\, x f$ = voltage rise above the 60 ~ spark-over voltage.

The crosses in Fig. 11 are calculated from this equation; the circles are measured values.

Equation (8) may also be written in terms of the time t, in which the sine wave reaches a maximum. Thus,

$$f = \frac{10^6}{4t}$$

Therefore, from (8)

$$e = \frac{4.4\,x}{t} + e_0 \tag{9}$$

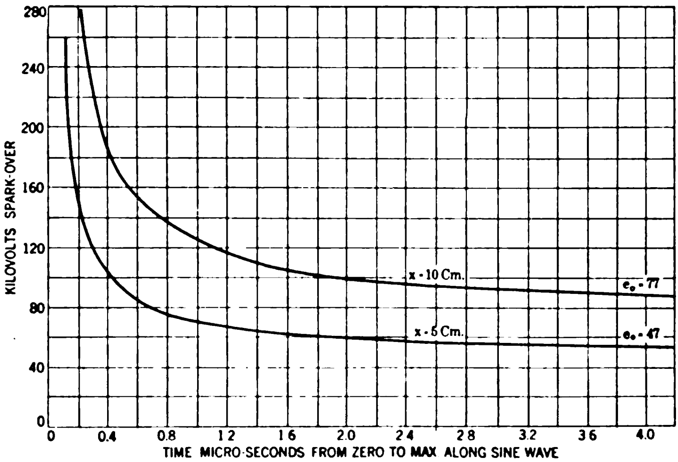


FIG. 12—NEEDLE GAP SPARKOVER—(KV. VS TIME.)

where t = time in micro-seconds for the impulse to reach maximum

$$t = \frac{4.4\,x}{e - e_0} \tag{10}$$

It is interesting to take a given spacing x, and determine t for various assumed values of e. Such curves are plotted in Fig. 12; e then is the voltage which is reached before spark-over occurs. This voltage starts from zero, and approximately follows a sine curve which reaches its maximum in the time t. It is probable that for needles, arc-over takes place after the maximum is passed. It can be seen that when the voltage does not rise rapidly above e_0 the time lag may be very great. The lag is greater at large spacings than small ones. At a given spacing the lag decreases with increasing rate of application, or α.

It is of interest to put t in terms of the rate of increase of voltage. Where α is the average rate of increase in voltage between zero and a maximum

$$\alpha = \frac{e}{t}$$

$$e = \alpha t$$

Substituting in (**9**) and solving for t

$$t = \frac{e_0}{2\alpha} + \sqrt{\frac{e_0^2}{4\alpha^2} + \frac{4.4\,x}{\alpha}} \qquad \textbf{(11)}$$

The time that the voltage is above e_0 may be found by subtracting the time required to reach e_0 from t. An equation containing α as in (**11**) would be of especial interest for voltages increasing along a straight line at a definite slope α. See data Table V.

In making impulse tests it is found that spark-over may not take place at every impulse, but perhaps at only one in ten, or one in fifty. To cause spark-over at every impulse it is necessary to increase the voltage, the amount depending upon the electrodes. The difference is minimum for spheres, and about 1 per cent. It may be 10 per cent for needles at very steep wave front. It is maximum for unsymmetrical electrodes. This will be discussed later. In all of these tests, unless otherwise stated, the gap was set so that one spark-over took place in ten impulses.

Spheres. Up to single half cycles of 1000 kc. sine waves, there is no great difference between the continuously applied and impulse spark-over voltages for spheres set below diameter spacing (except at very small spacings). Spark-over probably takes place near the maximum point of the wave. Such variations as occur are within the range of experimental error and thus cannot be accurately determined. When the spacing is less than the diameter of the sphere corona cannot form; spark-over occurs along a small tube of air directly connecting the nearest surfaces of the spheres. The spacing is small compared to needle gap spacing for the same continuously applied voltage setting. Before a needle sparks over, a large " sphere" of corona must first form. Much more energy is required than for the spheres. See Fig. 13 where this is illustrated diagram-

matically. When the sphere spacing is so large that corona precedes spark-over, the time lag or energy lag becomes appreciable. The condition at very small spacings is a special one and will be considered later. Thus, the sphere used within the proper limits is very " fast ", compared to points, and offers an accurate means of measuring transient voltages in the range covered above. The curves can be calculated by formulae already given.[5] Other electrodes have small time lag when arranged in such a way that the dielectric field is fairly uniform and corona formation does not precede spark-over.

The surfaces of the spheres may be roughened, to some extent, without greatly changing the impulse spark-over voltage. Drops of water or rain on the electrode surface greatly reduce the 60 ∼ spark-over voltage but reduce the impulse voltage to a much less extent.

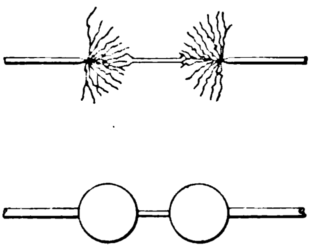


FIG. 13

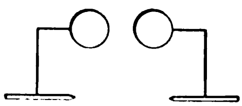


FIG. 14

SPARK-OVER OF GAPS IN MULTIPLE OVER VOLTAGES AT CONSTANT SLOPE

If sphere and point electrodes set to spark-over at the same 60 ∼ voltage are placed in multiple and a steep wave front impulse is applied, spark-over will always take place across the sphere gap. See Fig. 14. The sphere gap may now be set at a higher continuously applied or 60 ∼ voltage than the needle gap; an impulse, if of sufficiently short duration and high enough voltage, will spark-over the sphere gap before the needle gap has time to discharge. For instance, if a sphere gap is set for 84 kv. and a needle gap for 45 kv. at 60 ∼, an impulse equivalent to a single half cycle of a 177 kv. sine wave (of average front α = 730 kv. per micro-sec.) will always discharge across the sphere gap in spite of the fact that the needle gap is set at about half

5. F. W. Peek, Jr.,—" The Sphere Gap as a Means of Measuring High Voltages."—TRANS. A. I. E. E., 1913.

the 60 ~ voltage. These gaps share the impulses equally, only when the 60 ~ settings are 84 kv. and 42.6 kv. respectively. See Table V. This illustrates the difference in speed between a needle gap and a sphere gap. The impulse voltage is allowed to rise above the 42.6 kv. setting of the needle gap, and reach the 84-kv. setting of the sphere gap before the needle has time to spark-over. It is probable that, due to the relatively small lag of the sphere, the voltage rises slightly above 84 kv. See Fig. 15, where this particular case is illustrated. The needle gap spark-over voltage is 42.6 when the time is not limited; due to the time lag, spark-over does not take place when the voltage rises to 42.6 kv. but at some higher value, t_n micro-seconds later. The time, t_s, represents the small time of the sphere. With the above setting, spark-over may take place across either gap. If both the sphere gap and needle gap are now set at 42.6 kv. (60 ~) the sphere gap will spark-over t_s micro-seconds after this voltage

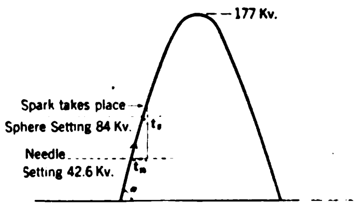


FIG. 15

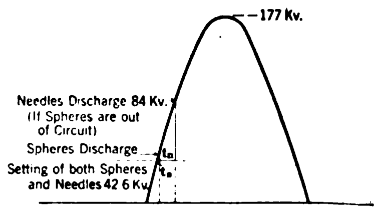


FIG. 16

occurs. The time, t_s, is relatively very small. The needle gap can then never discharge until the sphere gap is removed when spark-over will take place after the voltage has increased above 42.6 kv. along the wave for the time t_n. See Fig. 16. With the relative settings as in the first case above sparks may be made to pass at will over either the spheres or needles for the multiple gap by varying the wave front.

The data in Table V were obtained by applying over-voltages to sphere and needle gaps in multiple. The sphere gap was set at a given voltage, the needle gap was then adjusted until the applied impulse sparked an equal number of times between spheres and needles. A number of points were thus obtained. The waves made use of in obtaining different " fronts " are illustrated in Figs. 15 and 17. A maximum impulse voltage was always taken higher than the voltage setting of the sphere so that discharge took place on the rising wave where the front was still steep. This, then, approximates a voltage wave rising along

TABLE V

SPARK-OVER OF SPHERES AND NEEDLES IN MULTIPLE ON RISING WAVE

(SET TO SHARE IMPULSES EQUALLY ON VERY HIGH OVER VOLTAGES.)

Applied Impulse (Single half cycle 500 kc. sine wave.) max. kv.	Spaced to share impulses equally.		Spark-over voltage for these gaps at 60 ~ (max.)		Wave front (average) α = kv. per micro-sec.	Time from zero to sphere voltage. micro-sec.	Imp. Ratio
	Spheres 12.5 cm.	Needles	Spheres*	Needles			Needles
212	0.90	0.95	28.3	12.2	1080	0.027	2.30
"	1.95	2.25	56.5	26.4	940	0.060	2.14
"	3.07	3.90	84.0	41.7	900	0.094	2.00
"	4.27	5.70	113.0	53.5	850	0.132	2.10
"	5.63	7.20	141.0	62.1	770	0.180	2.25
"	7.20	10.00	170.0	76.0	710	0.240	2.24
177	0.90	1.00	28.3	12.8	810	0.035	2.20
"	1.95	2.45	56.5	28.2	790	0.071	2.00
"	3.07	4.15	84.0	42.6	730	0.115	1.97
"	4.27	5.80	113.0	54.0	660	0.170	2.10
"	5.63	9.40	141.0	73.0	590	0.240	1.95
107	0.90	1.05	28.3	13.1	495	0.057	2.16
"	1.95	2.75	56.5	31.0	430	0.131	1.82
"	3.07	5.00	84.0	49.0	345	0.242	1.71

*Also approximately impulse spark-over voltage See waves Fig. 17.

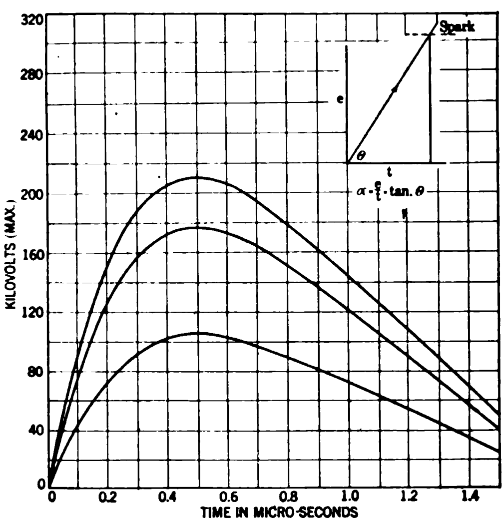


FIG. 17—IMPULSE WAVES—500 KILO-CYCLE

a straight line of a given slope. The sphere gap measures approximately the discharge voltage as shown in Fig. 15. The actual voltage is higher. The average rate of increase is in one case 1080 kv. per micro-sec. Note that for this particular case the sphere gap and the needle gap are set at *approximately the same linear spacing.* Thus, for steep enough wave fronts, the linear spacing determines where the discharge takes place for gaps in parallel, although the continuously applied spark

TABLE VI.
TRANSIENT CORONA
(Single half sine wave.)
CONCENTRIC CYLINDERS IN AIR

Bar = 76. cm. t = 25 deg. cent. δ = 1 Outer Cyl. rad. R = 8.8 cm.

Wire Radius	60 ~ tests.			Impulse tests.			
				Corona			
r cm.	Calc. corona kv. (max.)	Test corona kv. (max.)	Test spark-over kv. (max.)	A kv. (max.)	B kv. (max.)	Spark-over kv.(max.) 1 in 10	Single half sine wave frequency kilocycles
0.0318		13.4	135.0	13.8	15.6	100	100
				14.7	16.0	..	500
				15.1	16.1	..	900
0.0573	20.5	20.0	110.0	21.2	23.7	100	100
				22.0	24.0	..	500
				22.6	24.0	..	900
0.130	31.4	31.3	49.6	32.3	33.2	103	100
				33.5	34.0	..	500
				34.2	34.8	..	900
0.95	86.0	85.0	86.0	85.0	86.0	108	100
				87.0	87.5	..	500
				87.5	88.0		900
1.425	100	98.0	98.0	99.0	99.	110	100
				99.0	99.5	..	500
				100.0	101.0	..	900

voltages vary greatly. It is even conceivable that for very steep wave fronts a smaller gap would be necessary for needles than for spheres.

TRANSIENT CORONA AND SPARK-OVER FOR CONCENTRIC CYLINDER. + AND − TRANSIENT CORONA

Single half wave impulses were applied between concentric cylinders in a dark room. The impulse voltage was gradually

increased until visual corona started. The tests were conducted in much the same way as similar tests at 60 ~. The visual corona was quite definite although the impulse producing it in some cases reached its maximum value in approximately 3×10^{-7} seconds. A difference in the appearance of the corona was noted with successive impulses. There appeared to be two kinds. This should be the case, as the wire should average an equal number of times positive and negative. The voltage at which the first appeared is in Table VI, Column A; the second is in Column B. The difference in voltage is not great and can only be detected for small wires. The corona appears to start at the lowest voltage when the wire is negative, (0.0573 cm. diameter wire in 7.6 cm. cylinder, $\delta = 1$). When the

TABLE VI—*Continued*

Bar 76 cm. t = 25 deg. cent. δ = 1. Outer cylinder. R = 3.81 cm.

Wire Radius r cms.	60 ~ tests			Impulse tests			
				Corona			
	Calc. corona kv (max.)	Test corona kv. (max).	Test spark-over kv. (max.)	A kv. (max.)	B kv. (max.)	Spark-over kv. (max.)	f
0.0129	5.7	..	..	8.5	..	32.0	100
				9.2	..	68.0	500
				9.5	..	..	900
0.0318	12.3	12.0	49.0	13.4	14.7	33.0	100
				13.5	14.7	67.5	500
				14.5	15.0	..	900
0.0573	17.2	..	40.0	17.4	18.2	35.0	100
				20.0	20.5	66.0	500
				24.0	24.7	..	900
0.239	33.5	..	33.9	33.4	37.1	44.7	100
				37.0	38.9	63.7	500
					37.0	103.0	900
0.318	38.0	37.9	37.9	38.5	39.0	45.0	100
				39.5	40.0	64.0	500
				41.6	42.0	98.0	900
0.635	49.0	48.1	48.1	49.0	49.7	50.0	100
				50.0	50.5	62.0	500
				51.6	52.0	81.0	900
1.27	55.0	55.0	54.5	55.0	55.0	55.0	100
				56.0	56.0	57.0	500
				56.0	56.0	59.3	900

wire is + the corona seems to extend out to a considerable extent in fine streamers. The visual voltages for 900-kc. impulses were − 18 and + 19. The 60 ∼ calculated and measured values corresponding to the impulse measured values are given in Tables VI and VII, and plotted in Figs. 18, 19, 20 and 21. A comparison between the apparent impulse and the 60 ∼ corona voltages is best made

TABLE VII.

TRANSIENT CORONA AND SPARK-OVER.

Bar. = 76 cm. t = 25° C. δ = 1.

Radius Outer Cylinder R = 8.8 cm.

	Corona				Spark-over.			
Wire radius r cm.	g_v meas. 60 ∼ kv. per cm. (max.)	g_v cal. 60 ∼ kv. per cm. (max.)	g_v impulse kv. per cm.	Imp. ratio	Kilo-volts 60 ∼ (max.)	Kilo-volts impulse 1 in 10	Imp. ratio	Freq. kilo-cycles single half sine wave
0.0318	76.0		77.0	..	135.0	100	60 ∼ volts increased by "corona grading"	100
			82.0	..	..	..		500
			85.0	..	..	..		900
0.0573	70.0	71.5	73.0	1.02	110.0	100		100
			76.0	1.06	..	..		500
			78.0	1.09	..	..		900
0.130	56.9	56.9	59.0	1.04	49.6	103	2.08	100
			61.0	1.C7	..	..		500
			62.0	1.09	..	..		900
0.95	40.0	40.5	40.5	1.00	86.0	108	1.26	100
			41.	1.01	..	..		500
			41.5	1.03	..	..		900
1.425	38.4	39.0	38.2	0.98	98.0	110	1.12	100
			38.2	0.98	..	..		500
			38.6	0.99	..	..		900

by referring to Fig. 21, where the ratios of impulse to 60 ∼ voltages (impulse ratios) are plotted. The percentage difference is not great except for small conductors; part of the difference may be due to difficulty in determining the exact starting point. The difference increases with decreasing time of application of the voltage. A 60 ∼ corona curve for a wire in a cylinder is plotted in Fig. 19. The variation in the apparent strength of air with

the conductor radius at 60 ~ and for a single half cycle sine wave 900-kc. impulse is given in Fig. 20. Comparatively small time lag should be expected in the first appearance of visual corona as it is essentially spark discharge over a short distance from wire to space, very similar to sphere spark-over. The " spark-over " may be considered as taking place from the con-

TABLE VII—*Continued*
TRANSIENT CORONA AND SPARK-OVER.
Bar. = 76 cm. t = 25° C. $\delta = 1$.
Radius Outer Cylinder. R = 3.81 cm.

Wire radius r	g_v 60 ~ meas. kv. per cm. max.	g_v 60 ~ cal. kv. per cm. max.	g_v impulse kv. per cm.	Impulse ratio	Kilo-volts 60 ~ (max.)	Kilo-volts impulse 1 in 10	Impulse ratio	Frequency
0.0129	110.0	108.0	114.0	1.05		32.0	60 ~ volts increased by "corona grading"	100
			126.0	1.16		68.0		500
			130.0	1.20		..		900
0.0318	83.0	85.0	88.0	1.03	49.0	33.0		100
			89.0	1.05	..	67.5		500
			95.5	1.12				900
0.0573		71.5	72.5	1.01	40.0	35.0		100
			83.2	1.16		66.0		500
								900
C.239		50.5	50.5	1.00	33.9	44.7	1.32	100
			56.0	1.11		63.7	1.88	500
						103.0	3.05	900
0.318	47.6	47.6	49.0	1.03	37.9	45.0	1.20	100
			50.0	1.05		64.0	1.70	500
			52.9	1.12		98.0	2.60	900
0.635	42.2	42.9	43.0	1.00	48.1	50.0	1.04	100
			44.0	1.02		62.0	1.29	500
			45.4	1.06		81.0	1.68	900
1.270	39.4	39.4	39.0	0.99	55.0	55.0	1.00	100
			40.0	1.01	55.0	57.0	1.04	500
			40.0	1.01	56.0	69.0	1.25	900

ductor to space through the " energy distance " or rupturing distance of $0.3\sqrt{r}$ cm. This is the finite distance over which air must be stressed at a gradient of 30 kv per cm. and above ($\delta = 1$) before corona can start.[6]

6. F. W. Peek, Jr.,—Law of Corona, I, II, III, A. I. E. E., TRANS., 1911, 1912, 1913.

F. W. Peek, Jr., Dielectric Phenomena in High Voltage Engineering, Chaps. III and IV.

The rupturing energy is small. For very small wires, where the field is quite irregular, the time lag becomes appreciable.

For complete spark-over from wire to cylinder considerable

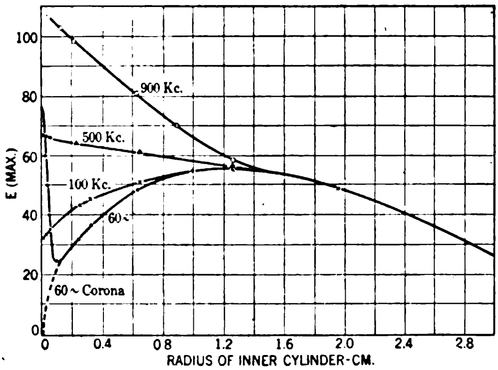


FIG. 18—SPARKOVER CURVES FOR CONCENTRIC CYLINDERS IN AIR—
$R = 3.81$ $\delta = 1.00$

energy must be expended in forming a cylinder of corona, when the field is such that corona precedes spark-over. The phenomena may be thought of roughly, as a succession of corona break

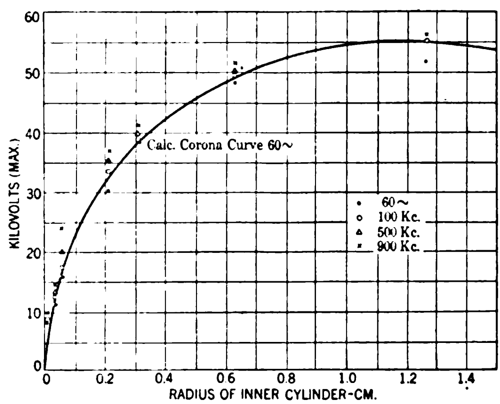


FIG. 19—SIXTY ~, AND TRANSIENT CORONA CURVES FOR CONCENTRIC CYLINDERS IN AIR

downs. The condenser charging current flows through the gradually forming corona. With a wire in a cylinder, corona cannot form when $\frac{R}{r} < \epsilon$.[7] The first evidence of stress is

7. F. W. Peek, Jr.,—Law of Corona II,—A. I. E. E., TRANS. 1913.

spark-over. Thus, there should be considerable lag when $\frac{R}{r} > \epsilon$ or for small wires, and the impulse spark-over voltage should be higher than the 60 ~ spark-over voltage. Data in

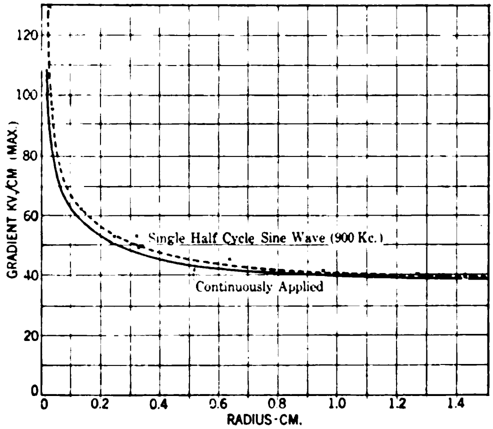


FIG. 20—CORONA GRADIENT CURVES FOR CONCENTRIC CYLINDERS—
$R = 3.81$ $\delta = 1.00$

Table VI and Figs. 18 and 19 show this to be the case. The exception is for *very small* wires when the 60 ~ spark-over voltage becomes quite high. This is due to the grading effect of corona on the wire enclosed in a cylinder.[7] There is, naturally, no such effect on a single impulse.

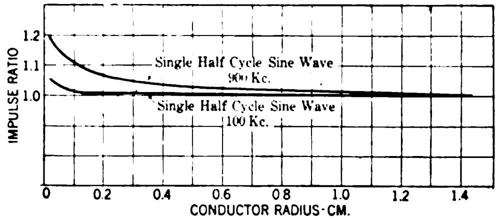


FIG. 21—AVERAGE IMPULSE RATIO OF CORONA ON WIRES— $\delta = 1.00$

The spark-over voltages in Table VI correspond to one spark-over in ten impulses. There is very little difference in the voltage for one discharge in a hundred applied impulses and one in ten; for ten discharges in ten impulses a considerable increase in

voltage is required above that for one discharge in ten impulses for some electrodes. This is especially so with dissimilar electrodes as the difference in spark-over when the wire is + and − then increases this effect. The range for various gaps is given in Table VIII.

In Table IX are spark voltages (1/10) for the wire, positive and negative. Spark-over takes place at a lower voltage when

TABLE VIII.

VARIATION IN SPARK DISTANCE WITH CHANGE IN RATIO OF NUMBER OF SPARK-OVERS TO NUMBER OF APPLIED IMPULSES

500 Kilocycles Impulse Sine Wave. $e/E = 0.43 = K$

Single half cycle applied impulse kv.	Impulse gap		Ratio No. of spark-overs to No. of applied impulses.	Max. Variation in 60 ~ kv. setting. between 1/10 and 10/10
	Spacing cm.	Corresponding 60 ~ kv.		
	25-cm. sphere gap.			
20	0.80	20.0	1/10	2%
20	0.75	19.5	10/10	
40	1.80	40.0	1/10	1%
40	1.75	39.5	10/10	
80	4.10	80.0	1/10	1%
80	4.00	79.0	10/10	
	2/0 needle gap.			
20	1.17	10.5	10/10	
20	1.35	12.0	10/20	22%*
20	1.60	13.5	4/40	
40	2.70	22.0	20/20	
40	3.00	24.0	10/20	14.7%
40	3.30	25.8	2/20	
80	5.40	37.0	20/20	
80	5.80	38.5	10/20	8.7%
80	6.25	40.5	2/20	

*Difference decreasing with increasing spacing.

the wire is positive. The impulses used in this test were obtained by placing a point and plate at gap A. The generator was connected for 500 kc., but a good impulse was not obtained as there was somewhat of an oscillation; the general characteristics of the + and − discharge are shown, however. The ***spark-over*** voltages given in Table VI are the minimum ones, and are, therefore, for the case when the wire is positive.

In appearance, the + and − corona of transients seems to be similar to that at 60 ~. The impulse positive visual corona from points extends out farther than the negative in the same

TABLE VIII.—*Continued*
CONCENTRIC CYLINDERS.
$R = 3.81$ cms.
500 Kilocycle Impulse Sine Wave.

Wire radius r cm.	Impulse kv. kv. (max.)	Ratio of No. spark-overs to No. of applied impulses.	Max. variation in spark-over kv. bet. 1/10 and 10/10
0.0318	67.0	2/20	
	83.0	10/20	32%
	99.0	20/20	
0.128	63.5	2.20	
	79.0	10/20	30%
	90.5	20/20	
0.239	63.0	1/10	
	75.0	10/20	26%
	85.3	20/20	
0.635	61.0	2/20	
	65.0	10/20	16%
	73.0	19/20	
1.27	56.0	2/20	
	58.2	10/20	7%
	60.3	20/20	
1.59	54.0	2/20	
	55.7	10/20	4.5%
	56.5	20/20	
900 Kilocycles Impulse Sine Wave			
0.239	105.0	1/10	
0.635	82.0	4/40	20%
	95.0	10/20	
	102.0	20/20	
1.27	55.9	2/20	
	59.2	10/20	11%
	62.6	20/20	
1.59	54.3	2/20	
	57.6	10/20	10%
	61.0	25/25	

manner that it does at 60 ~. This is of great interest; it means that with transients, as with steadily applied voltages, a considerable part of the air around points must be brought up to ionic saturation, or brushes must form, before spark-over can result.

Initial Ionization

It was expected that the degree of initial ionization in the vicinity of the electrodes would have a considerable effect upon the spark-over voltage. This was not found to be the case for electrodes in general. The reason was apparent after the corona tests were considered. Take, for instance, a small wire in a cylinder. Corona must form before spark-over can take place. It has been shown that the voltage rise above the continuously applied for the first appearance of corona on impulses is small.

TABLE IX.
POSITIVE and NEGATIVE SPARK-OVER.
(Dissimilar Electrodes.)

Wire in Cylinder. $R = 3.81$ cm.

Radius cm.	Voltage kv. wire +	Voltage kv. wire −	Per cent difference
1.27	57	57	0
0.187	51	58.5	15
0.0318	49.8	60.6	22

Point and Plate. Spacing cm. when point is +	Point and Plate. Spacing cm. when point is −
5.15	3.05

Approx.—500 kilocycle wave.

The time lag of the first appearance of corona is thus small compared to the time lag of the final spark discharges. The start of corona supplies greater " initial ionization " for the final spark than can generally be supplied externally by the action of ultraviolet light, X ray, etc. Such external means undoubtedly decrease the time for the first appearance of corona. This time is, however, generally too small to be detected, except for instance, in the case of very small wires. The spark-over in more or less uniform fields, as those around spheres, is probably affected by initial ionization but the total spark lag is so small that it is

difficult to measure. It is probable that the effect of "initial ionization" can be detected if the voltage is applied very gradually (a flat wave) *never rising greatly above the continuously applied break-down voltage.* This particular effect should be more pronounced where the molecular spacing becomes appreciable compared to the electrode spacing (at low density). For such a condition, the effect may be considerable as the percentage ionization supplied may approach ionic saturation. The chances of ions appearing between the electrodes is also greater with large initial ionization.

Steep wave front impulse tests were made ($\delta = 1$) with red hot wire loop electrodes, points and small spheres upon which ultraviolet light was directed, small spheres in a tube connected to an ozonator, points from which 60 ~ brush discharge took place, etc., without appreciable difference in spark-over voltage due to these various means of ionization. One striking test may be made by setting a point gap at a given voltage and causing an oscillation to play continuously across it. If a sphere gap set at the same 60 ~ voltage as the point gap, or even at a higher voltage, is suddenly placed in multiple with the point gap, the discharge will leave the point and take place across the sphere gap, although the point was previously ionized by the spark discharge.

Effect of Air Density on Transient Corona and Spark-Over

The transient corona and spark-over voltages decrease with decreasing air density (from $\delta = 1.00$ to $\delta = 0.05$)[8] in much the same way as at 60 ~.[9] Fig. 22 shows the variation of 60 ~ corona and impulse corona (900 kc. and 100 kc.) with air density. A small wire is used for illustration as otherwise the curves practically fall together. It is probable that the apparent in-

8. $$\delta = \frac{3.92b}{273 + t}$$

where b = barometric pressure in cm.
t = temperature degrees centigrade.

δ is the relative air density as a fraction of the density at 76 cm. pressure and 25 deg. cent.
where $\delta = 1$.

9. For method of test see Law of Corona III, F. W. Peek, Jr., Trans. A. I. E. E., 1913.

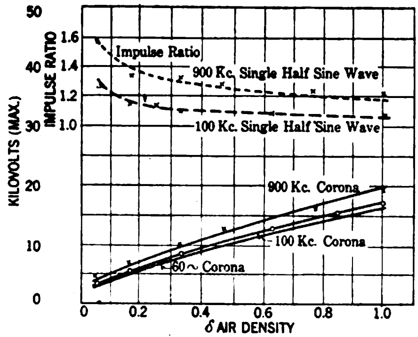


FIG. 22—VARIATION OF VISUAL CRITICAL CORONA VOLTAGE WITH AIR DENSITY—WIRE RADIUS = 0.0573 CM.

TABLE X.

EFFECT OF AIR DENSITY ON TRANSIENT CORONA AND SPARK-OVER

Concentric Cylinders[1]

Outer cylinder radius, R = 3.08. Inner cylinder, r = 0 0573 cm.

Corona					Spark-over				
Meas 60 ~ kv. max.	Cal. 60 ~ kv. max.	Impulse kv. max.	Impulse ratio	δ	60 ~ kv. max.	Impulse kv. max.	Impulse ratio	δ	Single half sine freq. kilo-cycles.
2.8	2.75	3.5	1.27	0.064	..	10.7	..	0.064	100
4.8	4.80	5.5	1.15	0.160	7.0	13.0	1.86	0.160	"
6.0	5.95	6.65	1.13	0.248	9.3	15.5	1.67	0.248	"
7.6	7.57	8.4	1.10	0.330	11.0	17.5	1.59	0.330	"
11.6	11.60	12.7	1.09	0.630	16.6	27.3	1.65	0.630	"
14.4	14.40	15.5	1.07	0.847	20.2	30.2	1.50	0.847	"
16.2	16.20	17.2	1.06	1.00	22.5	31.9	1.42	1.000	"
2.6	2.58	4.0	1.55	0.051	..	28.5	..	0.040	900
4.8	4.86	6.5	1.34	0.166	5.0	31.0	6.2	0.085	"
7.6	7.60	10.1	1.32	0.333	7.5	37.0	4.94	0.173	"
9.5	9.50	12.1	1.28	0.465	13.3	47.0	3.54	0.440	"
13.5	13.30	16.3	1.23	0.765	15.8	53.0	3.35	0.590	"
16.2	16.20	20.0	1.23	1.00	18.8	60.0	3.19	0.765	"
					22.5	67.5	3.00	1.00	"

1. Tests made in a metal lined glass tube.

crease in the strength of air for transients may be taken care of in the law for the visual gradient as follows.

$$g_v = g_0\,\delta\left(1 + \frac{0.308}{\sqrt{\delta\, r\, \phi\,(\alpha)}}\right)\phi\,(\alpha) \qquad \textbf{(12)}$$

When α is the steepness of the impulse. The impulse ratio increases with decreasing air density. See Table X.

TABLE X—*Continued*

Corona					Spark-over.				
Meas. 60 ~ kv. max.	Cal. 60 ~ kv. max. m_v = .94	Impulse[2] kv. max.	Impulse ratio measured values.	δ	60 ~ max. meas.	Impulse kv.	Impulse ratio meas. values.	δ	Single half sine kilo-cycles.
Out cylinder radius, R = 3.08 cm. Inner cylinder, r = 0.635 cm.									
7.3	7.7	8.5	1.16	0.127	7.3	8.5	1.16	0.127	100
13.0	13.0	14.9	1.14	0.253	13.0	14.9	1.14	0.253	"
15.0	15.3	16.6	1.11	0.309	15.0	16.6	1.11	0.309	"
17.0	16.8	18.3	1.08	0.350	17.0	18.3	1.08	0.350	"
24.0	23.8	24.5	1.02	0.535	24.0	24.5	1.02	0.535	"
29.0	29.0	28.9	1.00	0.702	29.0	28.9	1.00	0.702	"
34.5	35.5	34.5	1.00	0.863	34.5	34.5	1.00	0.863	"
39.0	40.3	40.5	1.03	1.002	39.0	40.5	1.03	1.002	"
Outer Cylinder radius, R = 3.08 cm. Inner Cylinder, r = 0.635 cm.									
3.5	3.9	8.6	2.46	0.049	3.5	20.3	5.80	0.049	900
9.0	9.8	11.9	1.31	0.165	9.0	25.0	2.78	0.165	"
14.0	14.1	17.3	1.23	0.280	14.0	30.5	2.18	0.280	"
21.2	21.2	22.5	1.07	0.462	21.3	37.6	1.77	0.462	"
26.2	26.3	28.0	1.06	0.604	26.0	43.5	1.67	0.604	"
32.0	32.2	35.6	1.01	0.773	32.0	48.5	1.52	0.773	"
39.0	40.3	40.2	1.00	1.00	39.0	52.5	1.34	1.00	"

2. Corona and spark-over practically coincident. δ = Relative air density.

$$\delta = \frac{3.92\,b}{273 + t}$$

3. Measured 60 ~ corona values were used in determining the impulse ratio. The calculated values are only approximate as it was difficult to exactly center the 0.635 cm. rod.

The 60 ~ and impulse spark-over voltages for a wire in a cylinder are shown in Fig. 23. The data are given in Table X. The impulse ratio for spark-over increases with decreasing pressure.

Spark-over-air density data for needle gaps are given in Table XI. It is difficult to get consistent results with needle gaps enclosed in a tube on account of the corona before spark-over.

Spark-over-air density curves for sphere gaps are given in Figs. 24 and 25. The impulse curves follow closely the 60 ~ curves. The impulse ratio is very nearly unity over a great range of δ. Spheres, therefore, within the limit prescribed for

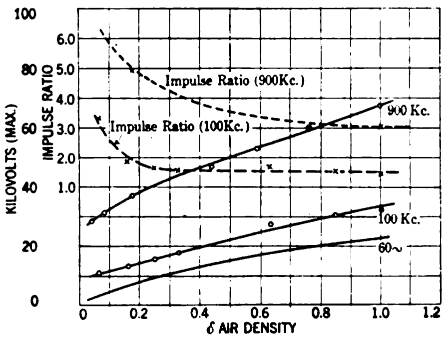


FIG. 23—VARIATION OF SPARKOVER WITH AIR DENSITY WIRE IN CYLINDERS — R = 3.08 CM.—r = 0.0573 CM.

TABLE XI.
EFFECT OF AIR DENSITY ON TRANSIENT SPARK-OVER BETWEEN NEEDLES.[1]

Spacing cm.	δ	Impulse kv. max.	60 ~ kv. max.	Impulse[1] ratio	Single half sine kilocycles
5 cm.	1.00	102.0	54.0	1.89	500
"	0.85	99.0	53.5	1.85	"
"	0.74	94.5	53.0	1.78	"
"	0.66	90.0	52.5	1.72	"
"	0.50	77.5	51.0	1.52	"
"	0.38	64.2	49.2	1.31	"
"	0.27	48.7	48.0	1.01	"
"	p.16	33.8	45.0	0.76	"
"	0.05	14.2	....	....	"
3 cm.	0.16	15.8	22.2	0.71	500
"	0.44	35.7	30.5	1.17	"
"	0.64	43.7	32.5	1.34	"
"	0.74	48.0	33.5	1.43	"
"	0.79	50.0	33.8	1.48	"
"	1.00	54.0	34.0	1.58	"

Tests made in glass tube.

1. These results are quite erratic, probably due to the effect of the brushes playing on the enclosing walls of the glass cylinder. For this reason accuracy is not claimed.

testing may be used to measure transient voltages over a wide α and δ range without correction to the 60 ~ curve.[10] It is

10. For method of obtaining low air density see " Effect of Altitude on the Spark-over of Leads, Insulators and Bushings." F. W. Peek, Jr., A. I. E. E. PROC., Dec. 1914.

probable that the expression for apparent strength of air around spheres should be modified for transient voltages as follows:

$$g_v = g_0\,\delta\left(1 + \frac{.54}{\sqrt{\delta\, R\, \phi(\alpha)}}\right)\phi(\alpha) \qquad (13)$$

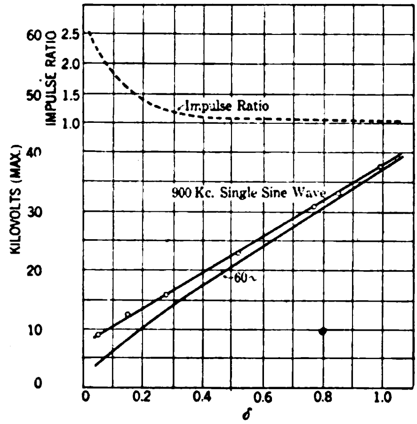


FIG. 24—SPARKOVER OF 2.54 CM. SPHERES AT LOW AIR DENSITIES—SPACING = 1.27 CM.

$\phi(\alpha)$ has, however, no appreciable effect over the practical testing range.

The variation of the spark-over voltage of insulators with air density is shown in Figs. 26, 27 and 28. For a smooth insulator

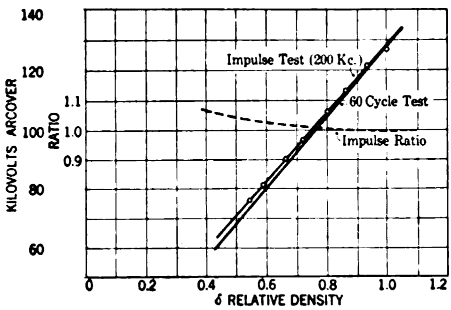


FIG. 25—SIXTY CYCLE AND IMPULSE ARCOVER AT LOW AIR DENSITIES 12.5 CM. SPHERES—GAP = 7.6 CM.

(Fig. 26) the impulse ratio is very nearly unity and does not change over the practical range. For insulators with petticoats and corrugations, the impulse ratio is high and increases with decreasing air density.

From a consideration of the above data it is seen that the transient spark-over impulse ratio does not change greatly with air density, where the field is fairly uniform so that corona does not precede spark-over. Where the field is such that it is necessary for corona to form in the path of the arc, the impulse ratio

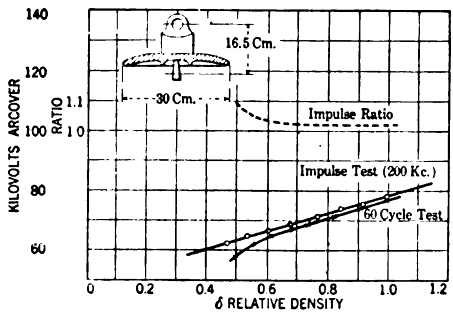


FIG. 26—SIXTY-CYCLE AND IMPULSE ARCOVER AT LOW AIR DENSITIES

becomes considerably higher at low air densities than it is at high air densities. The corona impulse ratio increases with decreasing air density; for large wires it is only appreciable for small values of δ; it may be considerable for small wires. The difference between the 60 ∼ and impulse spark-over and corona

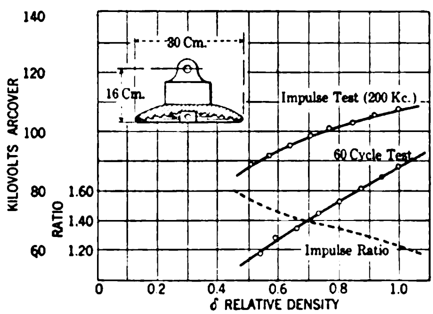


FIG. 27—SIXTY-CYCLE AND IMPULSE ARCOVER AT LOW AIR DENSITIES

voltages always increases with decreasing time of application.

The density tests shown in Figs. 22, 23 and 24, were made in glass tubes. The tubes were "aired out" after each test. It did not, however, seem to make any considerable difference whether or not this was done. At lower air densities this may make considerable difference, as the initial ionization may then

become a large percentage of ionic saturation. The chance of ions getting between the electrodes also depends upon the initial ionization. The tests shown in Figs. 25, 26, 27 and 28 were made in a large wooden cask.

Impulse Surface Spark-over—Impulse Spark-over of Insulators

If a dielectric, such as glass or porcelain, is placed between electrodes, arcs due to impulse voltages generally follow the surface. For smooth dielectrics the impulse ratio is nearly unity, even when the surface is fairly long and the fields not uniform. This is illustrated in a practical way in Fig. 26.

Where the surface has corrugations, petticoats, etc., the arc, generally, still follows the surface. The impulse ratio is, how-

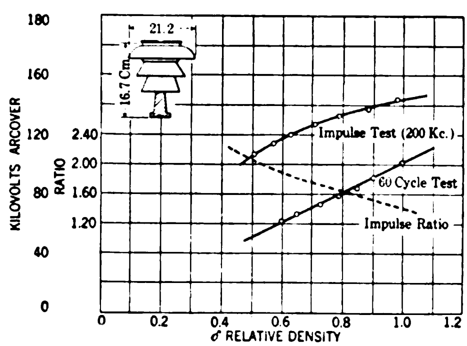


Fig. 28—Sixty-Cycle and Impulse Arcover at Low Air Densities

ever, higher, that is, greater time is required to cause spark over. See Figs. 27 and 28. For the insulator shown in Fig. 28 the impulse ratio at $\delta = 1$ (sea level) is 1.44. The 60 $\sim$ spark-over voltage is 100 kv.; the impulse spark-over voltage is 144 kv. At $\delta = 0.8$ (6000 ft. elevation) the impulse ratio is 1.75.

The time of spark increases when the field is such that corona must form in the path of the arc and when the length of surface is increased by corrugation.

As would be expected, the spark-over voltage of a given insulator varies with the polarity of the cap or pin. The test made on a pin type insulator and given in Table XII illustrates this.

Note that the 1/10 spark-over voltage corresponds to the (+) spark-over, and the 10/10 to the (−) spark-over. This would be expected. Impulse spark-over generally takes place at the

lowest voltage, or in the shortest time, when the electrode which is surrounded by the densest field is (+). In the above case, the porcelain is subjected to greater stress when the cap is (−).

TABLE XII.
EFFECT OF POLARITY ON INSULATOR SPARK-OVERS
200 kc.

60 ~ spark-over kv. max.	Impulse spark-over kv. varying polarity max.		Impulse spark-over kv. predetermined polarity. max.	
			Cap +	Cap −
98	1 spark over in 10 impulses	108	108	
	10 spark overs in 10 impulses	130		134

When a surface is placed between electrodes in a uniform field, or along a line of force, the 60 ~ spark-over voltage is lowered by true surface leakage. This is not generally the case with impulse voltages. The impulse spark-over voltage of an insulator is often not greatly changed by rain, although the wet 60 ~

TABLE XIII.
IMPULSE SPARK-OVER OF SUSPENSION INSULATORS WET AND DRY.

Ins. No.	Type	60 ~ arc-over (max.)		100 kc. impulse arc-over		500 kc. impulse arc-over	
		Dry	Wet	Dry	Wet	Dry	Wet
A	Two piece suspension with petticoats.	112	72	118	114	165	162
B	Two piece suspension with petticoats.	116	70	128	125	172	168

spark-over voltage may be 60 per cent of the dry spark-over voltage. See Table XIII.

Small Spacings or Air Films

At spacings smaller than the energy distance the apparent strength of air increases. For sphere gaps this apparent increase

in the strength of air starts when the spacing is less than 0.54 $\sqrt{R}$ cm.[11] The apparent strength of air at small spacings also increases for transient voltages; the increase, however, seems to be at a greater rate, as shown in Fig. 29, by the more rapid rise in the gradient with decreasing spacing. Data are given in Table XIV. The apparent strengths at 60 ~ and for impulses are represented by the corresponding tabulated gradients. These are the maximum gradients at the surface of the spheres. The impulse ratio is also tabulated. The low impulse voltages were obtained by connecting the gap across only part of the resistance. The results should be fairly accurate.

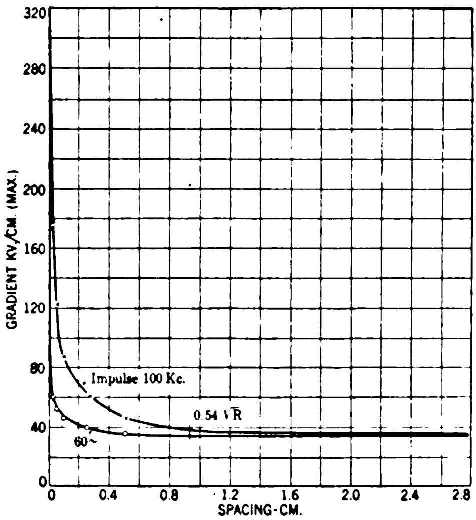


FIG. 29—STRENGTH OF AIR FILMS—BETWEEN 6.25 CM. DIAMETER SPHERES; $\delta = 1$

EFFECT OF TRANSIENT VOLTAGES ON OIL

It has been shown that for continuously applied voltages the mechanism of break-down in oil is very similar to that of air, and similar laws are obeyed.[12] Greater energy is required, how-

11. F. W. Peek, Jr.,—Law of Corona III., A. I. E. E., TRANS 1913.

12. F. W. Peek, Jr.,—High Voltage Engineering, *Journal, Franklin Institute*—December, 1914.

F. W. Peek, Jr.,—" Dielectric Phenomena in High Voltage Engineering " Chapter 6, page 163.

F. W. Peek, Jr.,—Law of Spark-over and " Corona " in Oil. *General Electric Review*—August, 1915.

ever, to rupture oil than air. There should, therefore, be a comparatively greater difference between the continuously applied and impulse voltages, that is, the impulse ratios should be higher than for air.

Impulse Ratios in Oil

In Table XV are 60 ~ and impulse spark-over voltages for disks, needles and spheres. In part of these tests the wave was only approximately known; on account of the high voltages necessary it was outside of the limits of the apparatus. It was

TABLE XIV.

TRANSIENT SPARK-OVER VOLTAGES AT SMALL SPACINGS.

(Between 6.25 cm. diameter spheres. $\delta = 1.$)

Spacing cm.	60 ~ Spark-over Volts max. kv.	60 ~ Spark-over Gradient max. kv. per cm.	100 kc. impulse Volts. kv.	100 kc. impulse Gradient kv. per cm.	100 kc. impulse Impulse ratio	900 kc. impulse Volts kv.	900 kc. impulse Gradient kv. per cm.	900 kc. impulse Impulse ratio
0.0025	0.50	196	0.78	305.0	1.57	0.81	325.0	1.64
0.0051	0.73	143	1.23	242.0	1.69	1.10	216.0	1.51
0.0076	0.90	118	1.70	212.0	1.80	1.78	235.0	1.98
0.0102	1.07	105	2.11	207.0	1.98	2.18	215.0	2.04
0.0127	1.17	92	2.44	192.0	2.08	2.55	200.0	2.18
0.025	1.52	60	4.50	178.0	2.95	5.00	198.0	3.04
0.051	2.62	52	6.15	122.0	2.35	8.50	168.0	3.25
0.102	4.62	46	8.75	87.0	1.90	12.80	126.0	2.77
0.25	9.77	40	14.90	61.0	1.52	21.50	84.1	2.20
0.51	17.50	36	22.50	46.0	1.28	28.50	56.0	1.63
1.27	39.20	35	42.00	37.0	1.06	47.00	37.0	1.20
1.90	57.50	35	57.50	35.0	1.00	62.50	36.0	1.09
2.54	88.50	35	88.50	35.0	1.00	90.00	35.0	1.02

Accuracy of impulse voltages best above 5 kv.

approximately equivalent to a half cycle of a 230 kc. wave. Between disks 0.5 cm. apart the impulse ratio is 3, whereas in air it is very nearly unity for the same spacing. Between needles at 4-cm. spacing, the impulse ratio is 3. For the same spacing and same impulse in air it is 1.25, that is, the voltage rise in oil is 200 per cent, in air 25 per cent. It will be noted that there is a considerable increase in voltage, or a high impulse ratio, for spheres. For sphere gaps in air the impulse ratio increases when the spacing is less than 0.54 $\sqrt{R}$ cm.; the increase is quite rapid when the spacing is less than 0.27 $\sqrt{R}$ cm. In oil the "energy distance" or rupturing distance is 2 $\sqrt{R}$ cm. A considerable

increase should, therefore, be expected in oil when the spacing is limited to less than 4 $\sqrt{R}$ cm. as was the case in this test. It is probable that the impulse ratio is quite appreciable for

TABLE XV.

IMPULSE AND 60 ~ BREAK-DOWN VOLTAGES IN OIL.

Spacing cm.	60 ~ kv. max.	Impulse kv. max.	Impulse ratio oil	Impulse ratio same spacing in air.	f
		Between disks 2.5 cm. diameter			
0.5	56.6	170	3.00	..	Approx. 230 kc.
		Between Needles.			
1	50	103	2.00	..	
2	69	157	2.20	1.20	Approx. 230 kc.
3	89	233	2.60	1.21	
4	108	321	3.00	1.25	
		2.54 Spheres—Small Spacings. Spacing less than 4 $\sqrt{R}$.)			
0.25	70	160	2.30	..	
0.50	100	245	2.45	..	Approx. 230 kc.
0.70	115	270	2.35	..	
1.00	140	285	2.05	..	

TABLE XV—*Continued*

IMPULSE AND 60 ~ BREAK-DOWN VOLTAGES IN OIL.

Between 2/0 Needles.

Needle spacing cm.	60 ~ spark-over kv. (max.)	Impulse kv.	Impulse ratio	f
0.32	28.0	36.5	1.30	100 kc.
0.64	40.0	70.0	1.75	(single half sine
1.27	63.0	128.5	2.04	wave.)
1.70	74.0	175.0	2.37	
2.00	81.0	..	..	
3.00	104.0	..	..	
0.20	20.0	36.0	1.80	500 kc.
0.32	28.0	64.0	2.30	(single
0.42	31.5	92.0	2.92	half sine
0.56	37.0	121.5	3.29	(wave.)

sphere gaps in oil even when the spacing is not limited. Results are also given, at somewhat lower voltages, where the waves are accurately known. See Fig. 30. Higher break-down

voltages for impulses result partly because moisture particles do not have time to line up.

Comparison of the Effects of High Frequency, 60 ~ and Impulse Voltages

It is interesting to compare the effect on oil for continuously applied voltage (60~), high-frequency voltage from an alternator, high-frequency oscillatory voltages, and single impulse voltages. Such a comparison is given in Table XVI. These data show how necessary it is to state the kind of "high frequency." There is not a great difference in the breakdown voltage for the single

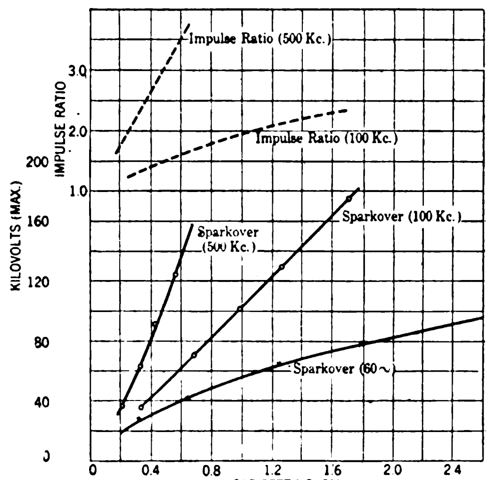


FIG. 30—TRANSIENT SPARK-OVER OF 2/0 NEEDLES IN NO. 6 TRANSIL OIL; TEMPERATURE 25 DEG. CENT.

impulse, and for the damped oscillation with wave trains following one another at the rate of 120 per second. The break-down voltage for continuously applied high frequency from an alternator is much lower than the 60 ~ break-down voltage. Here the effect of each half cycle is cumulative, and there is great local heating.

EFFECT OF TRANSIENT VOLTAGES ON SOLID INSULATION

Strength vs. Time of Application

In air and oil there is very little loss for continuously applied direct current or 60 ~ alternating current, until the gradient

is somewhere high enough to cause a local break-down in the form of corona or brushes. As heating due to losses is not an important factor the 60 ~ (max.) and d-c. break-down voltages are practically the same. For air, even at fairly high frequencies, the break-down voltage is not appreciably changed if the electrodes are smooth.[13] There is appreciable loss in solid insulation as soon as voltage is applied. Heating decreases the dielectric strength. A considerable part of the *voltage-time* curve is thus greatly affected by heating, especially at high frequency.

The data in Table XVII give an example of a voltage-time curve. See Fig. 31. The values from " infinite " time to 1/100 second were obtained at 60 ~. The data for the smaller values of time were obtained by impulse. It is probable that heating

TABLE XVI.

COMPARATIVE STRENGTH OF OIL FOR HIGH FREQUENCY, IMPULSE, OSCILLATORY, AND 60 CYCLE VOLTAGES

(Transil oil between flat disk terminals, square edges. 2.5 cm. diameter dia.; 0.25 cm. space.)

Break-down Gradients.

60 cycle kv. per cm. max.	Single impulse sine shape corresponding to 200 kilocycles. kv. per cm. max.	Damped oscillations train frequency 120 per second. Frequency 200 kilocycles kv. per cm. max.	High-frequency alternator 90 kilocycles. kv. per cm. max.
170	390	300	67.

is not an appreciable factor for values of time less than 60 seconds, on the 60 ~ test.

The general law (**14**) is followed by all solid insulations for low-frequency sine wave voltages and time of application from ∞ time to about 1/100 of a second. When voltages are applied for shorter time, by impulse, the apparent strength does not increase as rapidly with decreasing time, as equation (**14**) and Fig. 31 indicate. The small time limit depends upon the insulation. This seems to be due to the shattering effect of high over-voltages. When very high impulse voltages are applied, for instance, to porcelain tubes, these tubes may be completely shattered. Equation (**14**) is, however, useful in design at low frequencies over the above range. It should be

13. For a more complete discussion see, F. W. Peek, Jr.,—Dielectric Phenomena in High Voltage Engineering. Chapters III, IV, VI and VII.

noted that T in seconds times frequency is a count of the number of cycles that the voltage is applied.

$$g = g_v\left(1 + \frac{a}{\sqrt[4]{T}}\right) \text{ kv. per cm. max mum.} \qquad \textbf{(14)}$$

Where g = rupturing gradient.
g_v = constant for the insulation = break-down gradient for ∞ time.
a = constant of insulation.
T = time in micro-seconds.
Both g_v and a vary with the material, thickness temperature, etc.[14]

TABLE XVII.
STRENGTH vs. TIME OF APPLICATION.

Time sec.	Micro-seconds	Maximum kilovolt puncture.	Maximum g_v kv. per cm.
∞	∞	32.8	155
60	60 000 000	37.5	180
1.	1 000 000	49.3	235
0.1	100 000	61.0	290
0.01	10 000	85.0	405
0.001	1 000	113.0	540
0.0001	100	196*	935*
0.00001	10	310*	1480*

14 layers of impregnated paper between concentric cylinders. R = 0.67 cm., r = 0.36 cm.

$$g = \frac{e}{r \log_\epsilon \frac{R}{r}}$$

*Calculated.

For the insulation given in Table XVII,
g_v = 155
a = 15.8

Effect of Transient, High Frequency and 60 Cycle Voltages

There is a greater difference in the break-down voltages of solid insulations under different conditions, than for oil and air. This is so because of the high losses, etc., in solid insulation.[15]

14. For a more complete discussion see, F. W. Peek, Jr.,—" Dielectric Phenomena in High Voltage Engineering." Chapter VII.
15. *ibid.*

This difference is illustrated in Table XVIII. The impulse ratio for solid insulations seems to be of the same order as for oil, but in general slightly higher. The "one minute" 60 ∼ test is used to obtain the impulse ratios in Table XVIII. The importance of specifying the sort of "high frequency" and method in making tests is obvious.

Cumulative Effect of Over-Voltages of Steep Wave Front

If impulse voltages higher than the continuously applied break-down voltages are applied to oil and air, local ruptures which do

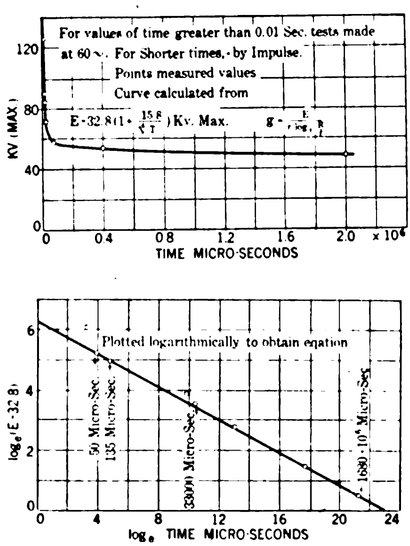


Fig. 31—Puncture Voltage vs. Time

14 layers of impregnated paper between concentric cylinders. R = 0.67 cm. r = 0.36 cm

not result in break-down may take place. The local break-down is automatically repaired by an inflow of new oil or air; the effects of the impulses are not cumulative unless they follow one another in succession at a very rapid rate, as high frequency from an alternator, or oscillations with high wave train frequency.

Voltages greatly in excess of the 60 ∼ puncture voltage may also be applied to solid insulation without complete rupture if the time of application is of sufficiently short duration. Such voltages injure the insulation by local shattering, cracking or tearing. Each additional impulse adds to this. For a very

high over-voltage such materials as porcelain may be badly shattered by a single impulse. A sufficient number will cause break-down; the effect is cumulative even if the time intervals

TABLE XVIII.

COMPARATIVE INSULATION STRENGTH FOR HIGH FREQUENCY, IMPULSE, OSCILLATION AND 60 CYCLE VOLTAGES.

Temperature 30 deg. cent.

60 cycles.		High frequency (alternator) 90,000 cycles.		Damped oscillation. Train freq. 120 sec. 200,000 cycles.		Single impulse sine shape, corresponding to half cycle of 200,000 cy.	Imp. ratio	Thickness cm.	Layers.
kv. per cm. (max.)		kv. per cm. (max.)		kv. per cm. (max.)		kv. per cm. (max.)			
Rapidly applied.	1 min.	Rapidly applied.	1 min.	Rapidly applied	1 min.				
Transil Oil between Flat Terminals—Square Edge. 2.5 cm. diameter—0.25 cm. space.									
170		67.	..	300	..	390	2.10	0.25	1
Oiled Pressboard. 10 cm. diameter Square Edge Disks in Oil.									
355.0	310.	95.0	72.0	370.	290.	720	2.3	0.25	1
395.0	370.	61.0	41.0	420.	240.	....		0.50	2
		25.0	17.60					1.50	3
Varnished Cloth. 10 cm. diameter Square Edge Disks in Oil.									
530.	465.0	195.0	176.0	..	..	1080.	2.26	0.06	2
420.	310.0	135.0	100.0	550	560	780.	2.50	0.15	5
420.	310.0	100.0	73.0	490	410	700.	2.25	0.25	8
330.	275.0	..	..	410	305	600.	2.20	0.36	12

"Rapidly applied" voltage brought to puncture value in a few seconds.

between applications are very great. For continuously applied high frequency or high train frequency, the high loss masks all other effects and causes low voltage break-down.

One example of the cumulative effect of impulses with long time intervals between applications is given in Table XIX. If the impulses are of still shorter duration a greater number are required to cause break-down at a given voltage. Insulations and line insulators are often gradually destroyed in this way.

TABLE XIX.

CUMULATIVE EFFECT OF OVER-VOLTAGES OF STEEP WAVE FRONT VOLTAGES ON SOLID INSULATIONS.

(Oiled pressboard 0.32 cm. thick between parallel plates 100 kc. sine impulse.)

Kv. maximum of applied impulse.	Number to cause break-down.
100	∞
140	100
150	16
155	2
165	1

Rapidly applied break-down at 60 ~ 100 kv. max.

If a very high voltage is applied, for instance, to a line insulator the number of applications to cause break-down will depend upon the nature of the arc-over path through the air, and the shapes of the caps and pin. To imitate this place a piece of oil pressboard between flat disks and find the number of high voltage impulses to cause puncture when the electrodes are shunted, (1) by a needle air gap, (2) by a sphere air gap, set at the same 60 ~ voltages. See Fig. 32. These data show in a striking way the relatively small lag of the sphere. When the electrodes were shunted by a sphere, break-down did not take place in 300 applications; when shunted by points with the same 60 ~ setting as the spheres, break-down occurred on a single application.

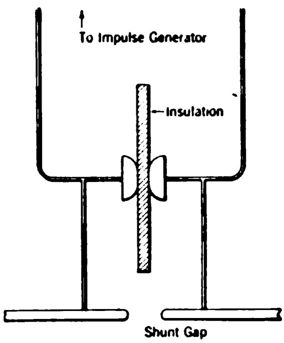


Fig. 32

SOME PRACTICAL ILLUSTRATIONS

In practise, lightning often discharges across a large spacing between bus bars, line insulators, etc., in preference to gaps which have a much lower 60 ~ setting. The reason for this is now apparent. As an example, a flat bus bar has a 60 ~ spark-over

voltage of 100 kv., while a point gap, shunting it, has a 60 ~ spark-over voltage of 50 kv. If the 60 ~ voltage is gradually increased to 50 kv. an arc-over will take place across the points. If, however, lightning causes the voltage to increase along a wave equivalent to a single half cycle of a 900 kc. wave with a 120 kv. maximum voltage, spark-over will occur across the bus-bars. This can be seen by reference to Fig. 10 or by calculation from equation (**8**). The point gap impulse spark-over voltage, for a 60 ~ setting of 50 kv., is 127 kv. The field is approximately uniform around the bus bars, and the spark-over voltage remains at approximately 100 kv. The points must be subjected to the voltage during the time that it increases from 50 kv., to 127 kv. The points are " slow." Thus, the 60 ~ spark-over voltage does not in general indicate the transient spark-

TABLE XX.

CUMULATIVE EFFECT OF IMPULSES.

Insulation between electrodes and shunted by gap, as in Fig. 32. Approx. 230 kc. impulse. Pressboard 0.32 cm. thick. 60 ~ puncture voltage 100 kv. max. Single impulse puncture voltage 140 kv. max.

Shunt across electrodes.	Impulse applied max. kv.	60 ~ setting of shunt gap (max.)	Number of impulses to puncture.
No shunt / No spark-over	350	..	1
Blunt points	350	120	1
Spheres	350	120	300 no puncture

over. Two gaps may be set at widely different 60 ~ voltages. A transient voltage high enough to spark-over either gap will select the one set at the highest voltage if that gap requires the least time under the circumstances.

Lightning travels along a transmission line at the rate of 3×10^8 meters per second. Thus a wave one kilometer in length passes a given point in 3.3×10^{-6} seconds or in 3.3 micro-seconds. By referring to Fig. 12 it can be seen that a wave of the above length might easily pass by a needle gap before discharge could take place. An insulator similar to the one shown in Fig. 26 would readily arc-over if the voltage were high enough. Corona would also form on the transmission line due to this wave and would help dissipate it to some extent. Damage might be done to line insulators as illustrated in Tables XIX and XX.

Various other practical applications of these data may be made.

THE GENERAL LAWS OFBREAK-DOWN OF DIELECTRICS BY TRANSIENT VOLTAGES

Air and other Gaseous Dielectrics

Energy is required to rupture dielectrics; this introduces a time lag. Thus, on account of this time lag, when voltage is applied at a very rapid rate, as by an impulse, spark-over does not occur when the continuously applied breakdown voltage is reached. The voltage " overshoots " this value during the time rupture is taking place. This excess, or rise, in voltage is greater the greater the rate of application.

If the voltage between electrodes is increased very gradually, never appreciably exceeding the minimum break-down voltage, a very long time may elapse before break-down occurs. If the field is fairly uniform a slight change in the conditions as initial ionization, or very small increase in voltage, may reduce this time from " infinite " to small finite time. The rise in voltage is not generally measurable for *continuously applied voltages* and the lag is, therefore, not noticed. The energy to rupture and, therefore, the required voltage rise and time depend upon the nature of the dielectric, the dielectric field, the shape and spacing of the electrodes, initial ionization, the rate at which the voltage is applied, etc., as follows: For formulas see text above.

1. If an impulse voltage rising at a given definite rate is applied between two electrodes spark-over will not take place when this voltage reaches the minimum continuously applied break-down voltage, but a finite time later. During this time the voltage has risen to some higher value before spark-over occurs. The ratio of the impulse spark-over voltage to the continuously applied spark-over voltage is termed the " impulse ratio "; the time interval between these voltages has been termed the " lag."

2. For a given rate of increase of voltage the rise above the continuously applied and, therefore, the impulse ratio and lag, is greater, the greater the non-uniformity of the field around the electrodes. For greatly non-uniform fields corona must always form in a space around the electrodes before spark-over can take place; energy must be expended in ionizing this space before the spark starts. For uniform and fairly uniform fields spark-over takes place without preliminary corona formation. For electrodes in general, non-uniformity of the field increases with spacing. Impulse ratio and lag, therefore, also increase with increasing spacing. In illustration of the above: for a given steep wave the lag of a needle gap may be so great that double the

continuously applied voltage is reached before spark-over occurs; the lag of a sphere is comparatively so small that the rise in voltage may be only one or two per cent.

3. For a given gap the rise, or excess, in the impulse spark-over voltage above the continuously applied voltage increases with the rate of application of the voltage. For the steeper wave fronts the break-down voltages are higher, but the time lag is less; less time is required to cause break-down at the higher average voltages. If the impulse is not steep the voltage rise is not great, but the lag may be comparatively long. ***The lag and voltage rise for a given gap are thus not constant but are dependent upon the rate of application of voltage; break-down is a matter of energy.*** If the rate of increase of voltage is great enough spark-over tends to be governed by linear spacing.

4. Corona is essentially spark-over from a conductor to space through the energy distance. ($0.3\sqrt{r}$ cm. for wire.) The lag of corona for impulse is thus small for large wires and in the order of that of sphere spark-over; for small wires, on account of the great non-uniformity of the field, the corona lag becomes appreciable and apparent by a rise in the impulse critical voltage.

5. Whether the degree of initial ionization in general measurably changes the rise in the impulse spark-over voltage over the continuously applied spark-over voltage for a given pair of electrodes seems to depend, to a great extent, upon whether the corona lag is measurable or apparent by a rise in voltage. Usually the corona lag is not measurable or appreciable compared to the lag of the final spark-over. Corona once formed supplies the initial " ionization " for the final spark. The effect of initial ionization is then generally not great, but may be so under certain conditions.

6. Impulse spark-over and corona voltages decrease with decreasing air desnity. The impulse ratio, however, increases with decreasing air density. It is probable that at very low air densities very high voltages are required to cause spark-over.

7. For dissimilar electrodes impulse spark-over takes place at the lowest voltage when the electrode in the densest field is positive. Corona appears to start at the lowest voltage on a small wire when the wire is negative.. For uniform and fairly uniform fields a difference between + and − rupturing voltages cannot be detected.

8. When the spacing is less than the energy distance, $0.54\sqrt{R}$ cm. for spheres) the lag increases.

9. The lag for spark-over on smooth dielectric surfaces is very small, but becomes greater as corrugations are added. The transient arc-over voltage is less affected by true surface "leakage" than the 60 ~ arc-over voltage.

Oil and Liquid Insulations

The transient break-down voltages for oil follow much the same laws given above for air. The energy and, therefore, the impulse ratio and lag are much larger for gaps in oil. The impulse ratio and lag are quite large for spheres. As the energy distance for spheres in oil is $4\sqrt{R}$, considerable lag is caused in this way even at fairly large spacings. For formulas see text.

Solid Dielectrics

1. Solid dielectrics require energy, and therefore, finite time for break down as do oil and air. The impulse ratio is generally highest for solid dielectrics.

2. The effect of over-voltages on solid insulations is cumulative. For formulas see text.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 16, 1915.

(*Subject to final revision for the Transactions.*)

EXPERIMENTAL RESEARCHES ON SKIN EFFECT IN CONDUCTORS

BY A. E. KENNELLY, F. A. LAWS AND P. H. PIERCE

ABSTRACT OF PAPER

The results are given of about one hundred series of tests, each covering a range in frequency up to about 5000 cycles per second, on the impedance of long loops of parallel conductors of different metals, sizes, and cross-sectional forms. The measuring apparatus is detailed. The theory of the skin effect in solid rods and in indefinitely wide flat strips is appended in a new and simplified form.

THE FOLLOWING researches were conducted, under an appropriation from the American Telephone and Telegraph Co., at the Massachusetts Institute of Technology in the Research Division of the Electrical Engineering Department, during the year 1914-15. In the early part of 1914, they were carried on under the directorship of Prof. Harold Pender. They date their origin, however, to M. I. T. thesis work undertaken in 1912-13.

Brief Early Historical Outline of Skin Effect Research. The first mathematical discussion of auto-distorted alternating-current density in a wire appears to have been given by Maxwell in 1873. Heaviside contributed an extensive mathematical literature to the whole subject in 1884-1887. J. H. Poynting also contributed to the mathematics of the subject in 1884-1885. Hughes developed the experimental side of the subject in 1886. Lord Rayleigh in 1886 first gave the formula for skin effect in an infinitely wide strip. Dr. H. F. Weber in 1886, J. Stefan in 1887 and O. Lodge in 1888 contributed further material. Lord Kelvin gave the expression in ber-bei functions in 1889. Hertz in 1889 and Sir J. J. Thomson in 1893 discussed the subject both from the experimental and mathematical standpoints. Mr. J. Swinburne used the term " skin-effect " in 1891.[1]

Manuscript of this paper was received June 25, 1915.

1. Discussion on the paper of Dr. J. A. Fleming, " On Some Effects of Alternating-Current Flow in Circuits having Capacity and Self Induction," Journal Institution of Electrical Engineers, London, Vol. XX, May 1891, p. 471.

Current-Distortion Effects. The phenomena to be discussed relate to distortions in the distribution of current-density over the cross-section of conductors, and may therefore be summed up under the title of "*current-distortion effects.*" These effects may be subdivided into three classes as follows:

1. An effect due to disturbance of current density in a conductor due to the alternating magnetic flux linked with the same, as in the case of simple, straight, round wires remote from return conductors. This is the "*skin-effect.*" It may be regarded as due either to imperfect penetration of electric current into the conductor, or to the greater reactance of the central core of the conductor with respect to the surface layer; whereby the current density is less on the inside than on the outside.

In a uniform solid round wire, the skin effect is symmetrical with respect to its axis. In solid wires of other than circular form, the skin effect is, in general, dissymmetrical.

2. An effect found in spiralled stranded conductors and due to the reactance of the spirals. This has been called the "*spirality effect.*"

3. An effect found in parallel linear conductors of any cross-sectional form when in proximity, owing to the alternating magnetic flux from one penetrating the other. This may be called the "*proximity effect.*"

The entire phenomenon of current-distortion effect, including the skin effect as a subtype, may nevertheless be referred to broadly as "skin effect" in conformity with current usage, unless a distinction is called for.

Apparatus Employed

The Mutual Inductance Bridge. Professor Hughes, on assuming the presidency of the Society of Telegraph Engineers in 1885, delivered an address on "The Self-Induction of an Electric Current in Relation to the Form of its Conductor." In carrying out the experiments there described, he used a form of bridge, which is diagrammatically shown in Fig. 1. Its peculiarity is that an e.m.f. is introduced into the detector circuit by means of a variable-ratio air-core transformer, or mutual inductance, shown at m in the diagram. The detector current can be brought to zero by adjusting the bridge arms and the mutual inductance. In the original paper, owing to an inadequate examination of the theory of this arrangement,

the results obtained were misinterpreted. Professor Hughes's paper precipitated a lively discussion, in which Lord Rayleigh, Sir Oliver Heaviside and Professor H. F. Weber participated.

One of the by-products of this discussion was the formulation of the complete theory of the Hughes bridge, by Professor Weber and Lord Rayleigh. Mr. Heaviside also showed that the arrangement used by Professor Hughes was not as simple in its action as that obtained, if the mutual inductance is inserted between either the supply circuit or the detector circuit, and one of the bridge arms. Both the Hughes and Heaviside bridges are shown in Fig. 1. The Heaviside bridge has been employed in all the work here reported.

The conditions for balance in the Heaviside bridge may be deduced thus:

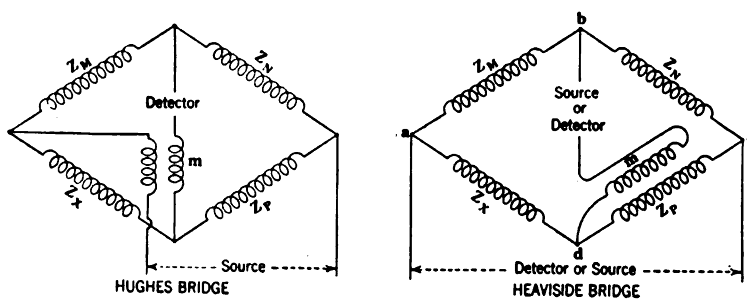


FIG. 1

The impedances of the bridge arms are denoted by Z and the mutual inductance by m. The r.m.s. current in any arm is denoted by I with the subscript designating the arm.

At balance, the currents in the arms M and N are equal, likewise those in X and P.

The potential difference between a and b, reckoned through the arm Z_M, must be the same as that via the arm Z_X, and the detector circuit, and that between b and c, reckoned through the arm N, must be the same as that via the detector circuit and the arm P. Consequently

$$Z_M I_M = Z_X I_X + jm\omega I_X \qquad \text{volts } \angle^{2} \quad (1)$$
$$Z_N I_M = Z_P I_X - jm\omega I_X \qquad \text{volts } \angle \quad (2)$$

2. The sign $\angle$ following the unit of an equation indicates that each side of the equation and every separate term thereof is to be considered as a "complex quantity," or plane vector.

Therefore

$$\frac{Z_M}{Z_N} = \frac{Z_X + jm\,\omega}{Z_P - jm\,\omega} \qquad \text{numeric } \angle \ (3)$$

In these experiments, an equal-arm bridge was used, with reference both to resistance and inductance; so that

$$Z_M = Z_N \qquad \text{ohms } \angle \ (4)$$

and the condition for balance becomes

$$Z_P - Z_X = 2\,jm\omega \qquad \text{ohms } \angle \ (5)$$

If R_P'', L_P'', R_X'' and L_X'', are the total resistances and inductances of their respective bridge arms, then

$$R_P'' - R_X'' + j\omega\,(L_P'' - L_X'' - 2m) = 0 \qquad \text{ohms } \angle \ (6)$$

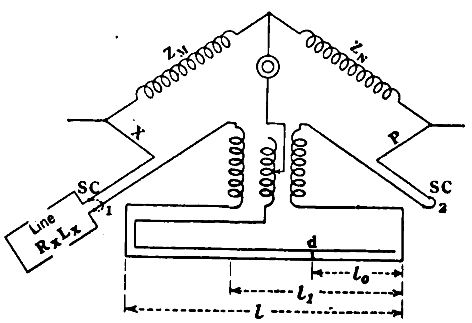


FIG. 2—ARRANGEMENT OF HEAVISIDE BRIDGE

Separating the quadrature components, we have

$$R_P'' = R_X'' \qquad \text{ohms } (7)$$

$$L_P'' = L_X'' + 2m \qquad \text{henrys } (8)$$

as the conditions for balance.

As we have to deal with small resistances, the most satisfactory method of varying the resistances of the bridge arms is to use a slide wire, as indicated in Fig. 2. Also, to eliminate extraneous resistances and inductances, it is advisable to work by the method of differences, two balancings being taken, the first, with the loop short circuited, the second, with the short circuit removed.

Actual Construction and Arrangement of the Bridge. To avoid trouble from stray fields, the various fixed coils of the bridge were wound on wooden rings, as indicated at *M*, *N*, *X* and *P*, Fig.

3. The turns were fixed in position, by being wound in carefully spaced saw-cuts. Eddy current effects in the mutual inductance (arms X and P) were avoided, by using for the primary winding a conductor made of 90 strands of No. 30 B and S enamelled copper wire, (diameter of each strand 0.255 mm.).

The primary winding of the mutual inductance was covered with a layer of tape. A thin, hard rubber ring with equally spaced radial saw-cuts served definitely to fix the secondary winding, which was carefully wound outside of the primary; so that it was spaced as nearly uniformly as possible, the aim being to obtain a uniform mutual inductance per turn. By means of the radial arm, A, the number of active, secondary turns can be varied form 0 to 89, by single-turn steps. Values

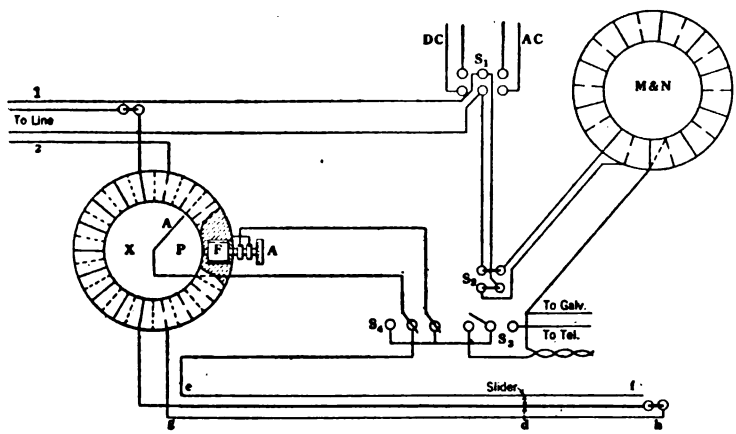


Fig. 3—Actual Arrangement of Bridge

intermediate between those given by two consecutive turns, are obtained by the use of the fine adjustment coil, shown at $F A$. This coil of three rectangular turns, each 2.5 cm. × 3.5 cm., is mounted within the wooden ring, as shown, and in such a manner that it can be rotated about its longer axis, to include a greater or lesser amount of the flux within the primary winding.

The change of mutual inductance due to turning the small coil, from the position of minus maximum to that of plus maximum, is somewhat greater than that due to one turn of the fixed secondary. The head, by which the position of the small coil is read off, is so graduated that one reads directly to tenths of a fixed turn, and, by estimation, to hundredths.

Twisted pairs of wires are used for all connections, and are

cleated to the table, so that they occupy fixed positions. The positions of the leads *e f* and *g h*, are fixed with reference to the slide wire. Any induction effects are thus rendered definite, and independent of the position of the telephone, which was used as the a-c. detector. Contact between the slide wire and the lead *e f* is made by a sliding spring clip. The functions of the switches shown in Fig. 3 are as follows:

By means of S_1 either direct or alternating current may be supplied to the bridge.

S_2 is a mercury switch, with ample contacts, by which the arms M and N may be reversed.

S_3 allows either the galvanometer or the telephone to be used as a detector, for d-c. and a-c. bridge balances, respectively.

S_4 reverses the terminals of the secondary winding of the mutual inductance.

In order to cover the entire range of the loop resistances in these experiments, it was necessary to use two different slide wires. Each wire was arranged together with its lead, *ef*, on a meter stick, so that the change from one to the other could be effected with little trouble. To avoid any indefiniteness due to contacts, the joints at the ends of the slide wire were always soldered. Table I gives the data of the slide wires used.

Check measurements of standard resistances and inductances were made at different times with the testing apparatus to make sure that it was in good order.

TABLE I. SLIDE-WIRE DATA.

Slide wire number	Gage B. & S.	Material	Resistance ohms per cm. $\frac{k}{2}$	Change in inductance by moving slider 2 cm. μ abhenrys
1	8	German Silver	0.000280	8.9
2	11	German Silver	0.000810	8.2

Change of inductance per turn of the mutual inductance winding,
$K = 1342$ abhenrys per turn.

The Loop of Conductors under Test. The conductors under test were arranged in a single long loop, with parallel sides. They were placed out of doors, about four meters from the ground, and

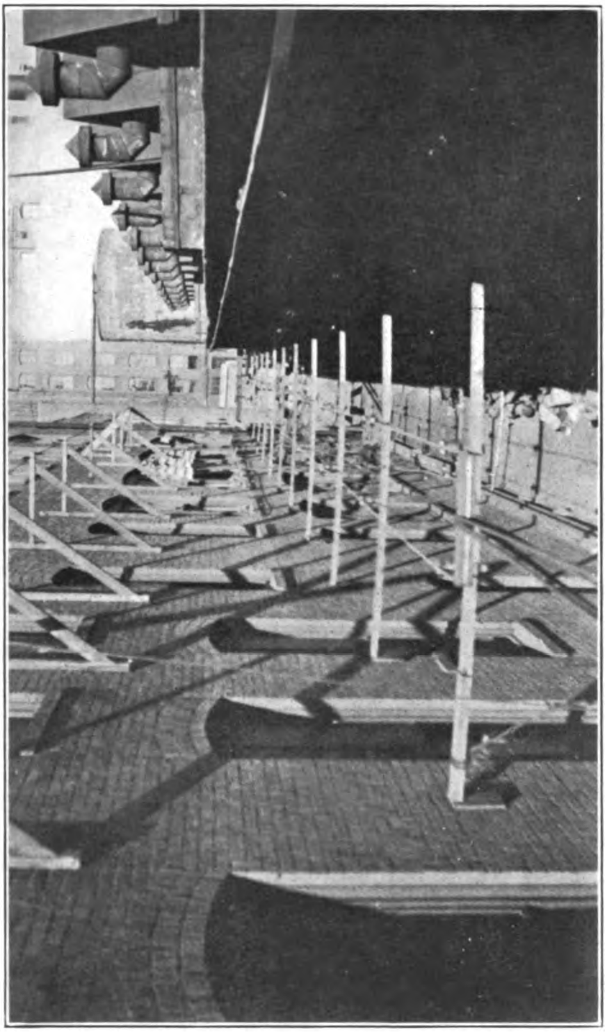


Fig. 4—View of Experimental Line

[Kennelly, Laws and Pierce]

rested either on glass insulators or on dry wooden supports, as occasion offered. By the use of tackles, the wires could be drawn taut, their positions being thus rendered definite. Fig. 4 is from a photograph of the loop, taken from one end of the alley. Fig. 5 (which is not drawn to scale) shows the arrangement of the line terminals. The short links allow the line to be transferred from position 1 to position 2 in the bridge, see Fig. 3. The link, mounted on the spring, is for the purpose of short circuiting the line, as above mentioned. Its action is controlled at the observer's position in the testing room by the use of the electromagnet *M*.

The observations are made as follows: The test loop is connected by the mercury cups to the bridge leads 1, (Fig. 3) while

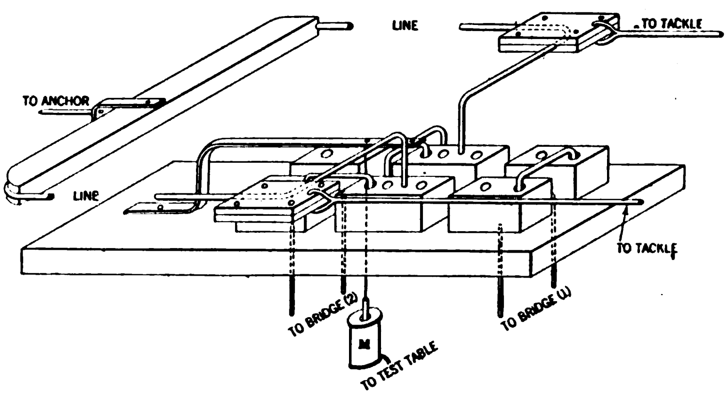


FIG. 5—LINE TERMINALS

the bridge leads 2, are short circuited. Two sets of readings are then made, first with direct and then alternating currents; one set with the line short circuited, and the other with the short-circuit removed. The ratio arms, *M* and *N*, are then reversed and the readings repeated. The line is then transferred to the other side of the bridge; that is, to the leads 2, while leads 1 are short circuited, and four more sets of readings are taken. The arithmetical mean result, given by the various sets of readings, is used in the computation.

During the balancings, the frequency is determined by the arrangement later described. A typical set of readings is shown in Table II. The theory of the a-c. bridge balance, applied to the actual construction, is given in Appendix I.

TABLE II.

Sample of a set of observations and calculations at one frequency in determining the skin effect of the No. 0000 solid copper wire, spaced 60 cm. between conductors

Temp. deg. cent.	Using Slide Wire No. 1.										
	Freq.	Arms	l_0'	l_1'	n_0	n_1	l_0	l_1	$l_1'-l_0'$ cm.	l_1-l_0 cm.	n_1-n_0 turns
25.6	1600	I	51.42	84.62	4.32	43.32	53.15	69.22	33.20	16.07	39.00
		II	54.25	88.40	4.47	43.58	58.15	74.35	34.15	16.20	39.11
		III	50.66	18.55	5.28	44.33	52.55	36.60	32.11	15.95	39.05
		IV	53.51	22.12	5.12	44.07	57.56	41.72	31.39	15,84	38.95
									32.71	16.02	39.03

D-c. Resistance $R = k(l_1 - l_0)$ **(A)**

$= 0.00056 \times 16.02 = 0.008972$ ohms

Skin Effect Resistance Ratio $\dfrac{R'}{R} = \dfrac{l_1' - l_0'}{l_1 - l_0} = \dfrac{32.71}{16.02} = 2.042$ **(B)**

Total Inductance of Loop $L = K(n_1 - n_0) + \mu\ (l_1' - l_0')$ **(C)**

$= 1342 \times 39.03 + 8.9 \times 32.71$

$= 52378 + 291 = 52669$ abhenrys

Calculation of Inductance of Loop

In the calculation of the inductance of the rectangle of conductor, the following formula was used. It is a slightly modified form of formula 107 by Rosa and Grover in the Bulletin of the Bureau of Standards, vol. 8, p. 155.

$$L = 4a\left[\log_e \frac{2b}{d} + \frac{b}{a}\log_e \frac{4b}{d\left(1+\frac{b}{a}\right)} - \frac{2b}{a} + \frac{d}{a}\right] + C(a+b)$$

$$= A + C(a+b) \qquad \textbf{(D)}$$

where a = cm. length of rectangle

b = cm. distance between axes of wires

d = cm. diameter of wires

A = abhenrys external inductance

$C = \dfrac{L_i'}{L_i}$ = skin effect inductance ratio

$C(a+b)$ = abhenrys internal inductance

L = abhenrys total inductance

In the sample case given above

$a = 2703.6$ cm.

$b = 61$ cm.

$d = 1.168$ cm.

$L = 51082 + 2764\ C$

At 0 frequency $C = 1$

and $L_i = 2764$

At 1600 ~ $L_i' = 52669 - 51082 = 1587$ abhenrys

$$\frac{L_i'}{L_i} = \frac{1587}{2764} = 0.5742$$

Electromagnetic Revolution-Counter. It was necessary for the observer to work in a soundproof room, distant from the machinery of the laboratory. Therefore, to facilitate the determination of the frequency, which must be measured with precision, the following arrangement was designed and constructed, with the object of determining by means of a stop watch, the time necessary for the completion of a given number of hundreds of revolutions of the generator. The device (Fig. 6) consists of two members,—a contact device which closes a circuit at the

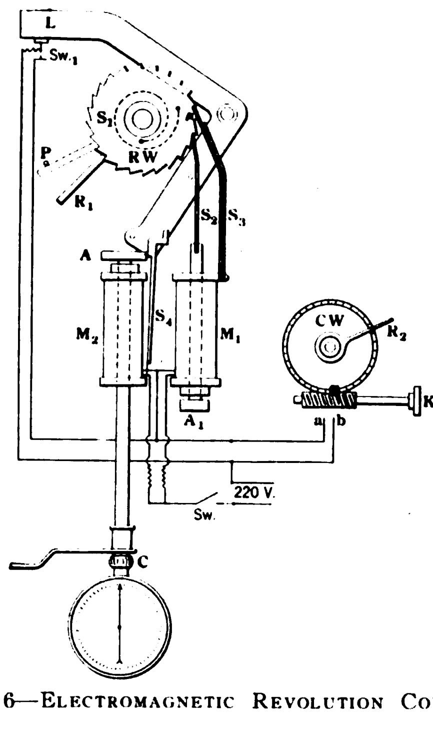


FIG. 6—ELECTROMAGNETIC REVOLUTION COUNTER

completion of each one hundred revolutions of the generator shaft, and a device for properly pressing the catch of the stop-watch. Fig. 6 is a schematic diagram of the apparatus.

The contactor is at *CW*. It consists of a worm and wheel, with a ratio of 100 to 1. The wheel carries an arm which, once every revolution, completes the circuit between *a* and *b*. The magnets M_1 and M_2 are thus energized. The gearing runs in a grease box, and a simple coupling *K*, permits of its ready attachment to any machine. The function of the magnet M_2,

is to press the catch of the stopwatch. The watch, being set at zero, on the first contact after closing the switch, $S\ W$, the armature A_2 is drawn down, and the stop watch is started. As A_2 moves down, the latch S_4 slips over it, and holds it in the depressed position. This prevents the succeeding contacts from stopping and restarting the watch. At the initial, and at every succeeding contact, the magnet M_1 is energized, and, by means of the ratchet spring S_2. advances the wheel $R\ W$ one tooth, in opposition to the spring S_1. S_3 is the retaining pawl, which bears so heavily on $R\ W$, that it also serves as a brake, and prevents sudden impulses of M_1 from advancing $R\ W$ more than one tooth at a time. After a definite number of contacts determined by the position of the pin P, the arm R_1 engages with S_4, and allows the armature A_2 to rise. At the next contact, the armature is again depressed and locked. The watch is thus stopped at, say, the completion of 1000 revolu-

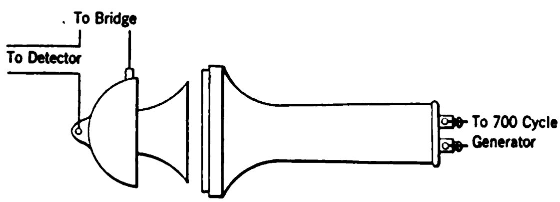


Fig. 7—Telephone Sensitivity Magnifier

tions of the generator. Further operation of the device is then prevented, for the arm R, is arrested against the spring, S_2.

The resetting is accomplished by depressing the lever L. The springs S_2 and S_3 and the latch are thus lifted, and spring S, returns the arm R, to the dotted position. At the same time $S\ W$, makes contact, M_2 is energized, and the watch reset to zero.

Detectors. The range of frequencies covered was from 60 to 5000 $\sim$. A pair of head telephones were used as the detector, both for direct and alternating currents. The telephones were sufficiently sensitive for the frequency range of from 200 to 5000 $\sim$. At 60 and with direct currents, the arrangement shown in Fig. 7 was used to increase the sensitivity. A telephone transmitter is inserted in the detector circuit. Immediately in front of it is placed a hand telephone, which is traversed by a current from a 700-cycle generator. It therefore emits a loud sound. The low-frequency current in the detec-

tor circuit is thus broken up into alternations of that frequency and the effective sensitivity of the telephone to low frequencies is greatly increased. This device is set up in a distant room, and is properly muffled, so that it does not disconcert the observer.

Generators. To cover the range of frequencies, from 60 to 5000 $\sim$, three motor-driven a-c. generators were employed; (1) for 60 $\sim$, a Mordey machine which forms a part of the regular equipment of the laboratory; (2) for the range 200 to 700 $\sim$; a small motor-generator set, originally designed for telephonic work; and (3) for the range from 1000 to 5000 $\sim$, a high frequency generator capable, at full speed, (3750 rev. per min.), of giving 10,000 $\sim$.

In all cases, speed variations were obtained by the use of resistances in series with the armature of the d-c. driving motor.

The waves of alternating current supplied by these generators to the Heaviside bridge were fairly sinusoidal. Although faint harmonic tones could often be detected in the observer's telephones, there was no difficulty in balancing the bridge to the fundamental tone.

Tests on Round Solid Copper Wires

Tests were made on a loop of two parallel copper wires, each No. 0000 A.W.G., diameter 0.46 inch (1.168cm.), cross-section 1.072 sq. cm., and also on two solid parallel aluminum wires of the same size.

Copper Wires. The loop of copper wire had a length of about 27 meters, differing slightly in different tests. The wire was provided in lengths of 20 feet (6.1 m.) in selected straight rods. Five tests were made at as many different spacings between the sides of the loop. These spacings or clearances between conductors, were 60 cm., 20 cm., 6.4 cm., 0.8 cm. and 0.03 cm. respectively. Scarfed soldered joints were made between successive rods. The measurements were made in each case at a time of day when the loop was not in sunshine, and when the loop was consequently at a fairly constant and observed temperature. The following Table III gives the results obtained in these tests, at the spacing of 60 cm. Column I gives the spacing, or the distance between adjacent surfaces of the two conductors in the loop. Column II gives the temperature of the wire, by thermometer observation at one point on the loop. Column III gives the frequency. Column IV gives the total

d-c. resistance of the loop between its terminals, in microhms or thousands of absohms. Column V gives the skin-effect resistance ratio of the wire in the loop, as obtained from bridge measurement at each frequency.[3] Column VI gives the corresponding computed resistance skin-effect ratio by formula (**71**). Column VII gives the ratio of observed to computed values, as appearing in V and VI respectively. Column VIII gives the total measured inductance of the loop, between its terminals, in abhenrys. Column IX gives the total inductance of the loop, within the substance of the wire, after deducting 51,082 abhenrys, the total computed external inductance, including end effect, in the loop. Column X gives the ratio of the internal inductance at each frequency, to the internal inferred inductance at zero frequency (2764 abhenrys) by dividing the entries in IX by 2764. The last column, No. XI, gives the same ratio as computed through formula (**76**.)

It will be seen from Column VII, that the observed skin-effect resistance ratio differs from the computed value by not more than 1 per cent at any of the observations. Also, comparing Columns X and XI, it will be seen that the skin-effect reactance-ratio, as observed, is in satisfactory agreement with the calculated value. The percentage agreement is not so close for the reactances as for the resistances; but the internal inductance, varied by skin effect, is only about 2 per cent of the total inductance measured, and consequently, the changes deduced in this small internal inductance cannot be predicted with the same precision as changes in the total apparent resistance. The results on this loop of solid round copper wires, at 60 cm. separating distance, are therefore in very satisfactory accordance with the Bessel-function theory as developed by Heaviside and Kelvin.

The test was repeated with the sides of the loop brought to a separating distance of 20 cm., by fastening the two wires to the edges of a wooden framework 20 cm. wide, and approximately 27 meters long. The same procedure was followed in the third and fourth tests, the wires being fastened to separating wooden strips at distances of 6.4 and 0.8 cm. apart, respectively. In a fifth test, the wires were separated only by a strip

3. In the discussion of skin effect, it is customary to express the conductance effect through the ratio R'/R. For some purposes, however, its reciprocal, the conductance ratio, R/R' is preferable. In this paper the customary expression is given throughout.

TABLE III.

SKIN EFFECT IN A NO. 000 SOLID COPPER CONDUCTOR OF DIAMETER 1.168 CM.

I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Spacing between wires cm.	Temp. degrees cent.	Freq. cycles per second	R_{dc} micro-ohms	$\frac{R_{ac}}{R_{dc}}$ observed	$\frac{R'}{R}$ computed	$\frac{R_{ac}}{R'}$ $\frac{\text{observed}}{\text{computed}}$	L total abhenrys observed	L_i abhenrys observed	$\frac{L_i'}{L_i}$ observed	$\frac{L_i'}{L_i}$ computed
60	23.5	60	8904	1.0038	1.0046	0.999	53912	2830	1.024	0.9977
	24.2	306	8915	1.111	1.108	1.003	53.767	2685	0.9714	0.9463
	25.0	888	8954	1.587	1.571	1.010	53.143	2061	0.7456	0.7311
	25.6	1600	8972	2.042	2.036	1.003	52.669	1587	0.5742	0.5599
	26.2	2040	8977	2.279	2.261	1.008	52.499	1417	0.5126	0.4959
	27.1	3065	9006	2.694	2.701	0.997	52.215	1133	0.4099	0.4071
	27.4	3950	8990	3.034	3.028	1.002	52.082	1000	0.3618	0.3595
	27.9	5000	9006	3.361	3.371	0.997	51.965	883	0.3195	0.3202

of thin paper, the wires being fastened together over the paper, by insulating tapes at frequent intervals.

The results of the successive tests are recorded in Table IV.

TABLE IV.—SKIN EFFECT IN A NO. 0000 SOLID COPPER CONDUCTOR

Spacing cm. between conductors	Temp. degrees centi-grade	Frequency cycles per second	R microhms	$\frac{R'}{R}$	L total abhenrys observed
2.0					
	17.2	60	8640	1.0058	41,874
	15.2	288	8518	1.106	41,698
	15.2	868	8500	1.584	41,099
	15.0	1663	8495	2.120	40,576
	14.9	2061	8512	2.313	40,437
	15.2	3063	8512	2.755	40,202
	15.4	3112	8440	2.781	40,149
	15.3	3860	8440	3.067	40,071
	15.4	5040	8456	3.446	39,910
6.4	18.5	60	8378	1.0087	30,528
	18.9	266	8388	1.100	30,320
	19.3	582	8383	1.354	30,038
	20.4	923	8434	1.640	29,728
	20.7	1465	8411	2.037	29,352
	20.9	2019	8316	2.344	29,108
	21.0	1992	8132	2.322	29,096
	21.0	3028	8132	2.851	28,819
	21.6	3960	8343	3.145	28,688
		5320	8472	3.558	28,546
0.8		60	8612	1.0124	15,894
		239	8612	1.132	15,602
		671	8596	1.604	14,793
	16.3	1068	8618	1.981	14,350
	16.5	1509	8624	2.330	14,007
	16.9	1991	8635	2.643	13,782
	17.2	1988	8602	2.638	13,722
	17.8	2486	8626	2.912	13,560
	18.0	3028	8642	3.179	13,301
	18.3	3880	8642	3.587	13,284
	18.4	4900	8654	3.995	13,127
0.03	21.1	60	8696	1.0172	10,379
	21.4	236	8700	1.244	9,851
	21.5	740	8716	2.231	8,143
	21.5	1000	8735	2.688	7,594
	21.2	1473	8724	3.460	6,889
	21.0	2038	8708	4.272	6,374
	20.9	3058	8716	5.522	5,805
	21.0	3918	8700	6.449	5,558
	21.1	5170	8729	7.512	5,297

At 20 cm. spacing, the skin-effect resistance ratio does not differ appreciably from the ratio at 60 cm. until the frequency of about 800 ∼ is reached. Above this frequency, the ratio rises slightly, but distinctly, above the 60 cm. ratio, and at 5000

~ exceeds the latter by 2.2 per cent. This increase is to be attributed to proximity effect; *i.e.* to the effect of the magnetic field from the parallel return conductor.

As the conductors were brought closer, Table IV shows that the skin-effect resistance ratio increased considerably, owing to proximity effect. With the separating distance of 6.4 cm., the rise in resistance ratio was still hardly appreciable below 800 ~, and only amounted to 3.3 per cent at 5000 ~. With a separation of 8 mm., however, the ratio increased markedly, being 1 per cent extra at 60 ~ and 20 per cent extra at 5000 ~. At the very small separating distance of about 0.3 mm., the ratio was greatly increased, being 1.3 per cent extra at 60 ~, 35 per cent extra at 400 ~, and 119.7 per cent extra at 5000 ~. While, therefore, to the ordinary light-and-power frequency of 60 ~, the proximity between going and return conductors has very little influence on the skin-effect resistance ratio R'/R of these rods, at higher frequencies, the degrees of proximity has a noteworthy effect on this ratio, at separations below 6 cm., as in cabled or flexible-cord conductors.

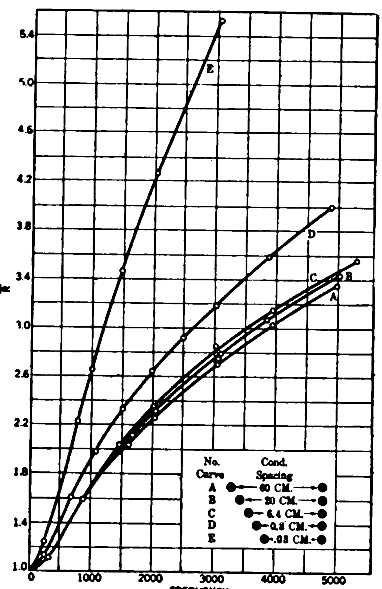


FIG. 8—NO. 0000 SOLID COPPER CONDUCTOR

Change of resistance with frequency for different spacing of conductors.

The ratios of the skin-effect on resistance at different loop widths to that at 60 cm. width are collected in Table V. It will be seen that beyond the frequency of 3000 ~, the ratio of increase due to proximity is but slightly affected by further increase in frequency. Thus, while between 60 ~ and 3000 ~, the effect of bringing the distance between going and returning conductors down to 8 mm. increases the skin-effect resistance ratio from 1.009 to 1.190 times what it would be at 60 cm., and further increase in frequency to 5000 ~ only increases the ratio from 1.190 to 1.201.

Fig. 8 shows the skin-effect resistance ratio R'/R for the data

contained in Tables I, II and III, with ordinates R'/R and abscissas impressed frequency.

In regard to parallel solid round wires, at 60 cm. separation,

TABLE V.—SKIN EFFECT IN A NO. 0000 SOLID COPPER CONDUCTOR

DATA TAKEN FROM CURVES SHOWING RELATIONS BETWEEN SKIN EFFECT AND SPACING OF CONDUCTORS FOR VARIOUS FREQUENCIES.

Frequency cycles per second	Spacing, cm. between wires	$\frac{R'}{R}$ resistance ratio	Ratio of skin effect to that at 60 cm. spacing
60	0.03	1.0172	1.013
	0.8	1.0124	1.009
	6.4	1.0087	1.005
	20	1.0058	1.002
	60	1.0038	1.00
400	0.03	1.590	1.353
	0.8	1.295	1.102
	6.4	1.184	1.008
	20	1.180	1.004
	60	1.175	1.00
1000	0.03	2.688	1.611
	0.8	1.928	1.154
	6.4	1.700	1.017
	20	1.690	1.012
	60	1.670	1.00
2000	0.03	4.210	1.870
	0.8	2.650	1.177
	6.4	2.335	1.037
	20.	2.295	1.019
	60.	2.250	1.00
3000	0.03	5.450	2.040
	0.8	3.185	1.190
	6.4	2.800	1.048
	20.	2.740	1.024
	60.	2.676	1.00
4000	0.03	6.530	2.14
	0.8	3.640	1.193
	6.4	3.164	1.038
	20.	3.112	1.021
	60.	3.048	1.00
5000	0.03	7.380	2.197
	0.8	4.040	1.201
	6.4	3.472	1.033
	20.	3.430	1.022
	60.	3.361	1.00

Mr. C. P. Eldred, in preliminary work, during 1914, on the same research, at the Massachusetts Institute of Technology, obtained observations over the range between 60 ~ and 5000 ~ of the skin-effect resistance ratio in wires of both copper and

aluminum, which check satisfactorily the Bessel-function calculations. The sizes of wire tested were No. 0 A.W.G. (diameter 0.325 inch 0.826 cm., 105,500 cir mils. 0.5345 sq. cm.) and also No. 0000 A.W.G. (diameter 0.46 inch 1.168 cm. 211,600 cir. mils 1.072 sq. cm.) in copper and in aluminum.

While, therefore, the Maxwell-Heaviside-Kelvin theory for solid round wires has been checked within the degree of precision of the observations, both for copper and aluminum, up to 5000 ~, 1.17 cm. diameter, and 60 cm. spacing, very considerable deviations from that theory have been found with closer spacings, owing to proximity effect. This deviation was predicted by Heaviside[4] in 1884. Up to the present time, the authors have not found a formula for skin effect in parallel round wires which will take the proximity effect into account.

Stranded Conductors. The stranded conductors tested were of copper and of aluminum.

Copper Stranded Conductor. The copper strand consisted of seven copper wires of the same size (diameter 0.442 cm.), six of these being spiralled around the central one, with a pitch of approximately 14.5 cm. The cross-section of one of these wires is 0.1532 sq. cm. and taking seven times this amount as the cross-section of the strand, we have 1.072 sq. cm. which is the same (to four digits) as that of a No. 0000 A.W.G. solid wire. The results of the tests on a loop of 31.5 meters of this stranded conductor are given in Table VI, for two different spacings; namely, 60.9 cm. and 2.4 cm.

Referring to the observations at 60.9 cm. spacings, it will be observed that the resistance skin-effect ratio R^1/R, at 60 ~, is 1.0052, representing an increase of only half of one per cent. At 5000 ~, however, this ratio increased to 3.54. In Fig. 9, curve B connects the observations here referred to. The broken curve A gives the corresponding skin effect for a solid conductor of equal cross-section, as taken from Tables I and II, or Fig. 8, using the same linear resistance for both the solid and stranded conductors. It appears, therefore, that above 1200 ~, the skin-effect resistance ratio of this stranded conductor was slightly greater than that of the equi-sectional solid wire, owing apparently to spirality effect, the difference increasing towards higher frequencies.

As is demonstrated in the Appendix, and has already been

4. Bibliography No. 2.

made known from earlier experimental work in this research,[5] the skin-effect impedance ratio, as well as its component ratios, is the same for a uniformly and symmetrically subdivided conductor, without twist or helical lay, as in the solid round conductor of the same material and cross-section. In any actual stranded conductor, however, whether of concentric-lay, or rope-lay, there is helical twist in some or all strands. This spiraling of some of the strands necessarily introduces an al-

TABLE VI.—SKIN EFFECT IN 7-STRAND COPPER CABLE
EQUIVALENT TO NO. 0000 SOLID WIRE.

I	II	III	IV	V	VI	VII	VIII	IX
						Calculated for Solid No. 0000		Ratio $\frac{\text{VI}}{\text{VIII}}$
Spacing cm.	Temperature deg. cent	Frequency	d-c. resistance ohms	$\frac{R'}{R}$	L, total abhenrys	$\frac{R'}{R}$	L, total abhenrys	
	12.0	60	0.00991	1.005	61,661	1.005	62,703	0.983
	25.7	207	0.01051	1.035	61,578	1.051	62,627	0.983
	27.0	475	0.01054	1.233	61,274	1.227	62,350	0.983
	26.8	925	0.01061	1.582	60.770	1.584	61,827	0.983
60.9	27.0	1468	0.01061	1.966	60,335	1.945	61,384	0.983
	27.0	2010	0.01063	2.295	60,053	2.236	61,118	0.983
	27.7	3065	0.01063	2.802	59,719	2.685	60,815	0.982
	27.5	3920	0.01064	3.151	59,539	2.989	60,673	0.981
	27.2	5040	0.01061	3.552	59,371	3.360	60,531	0.981
	20.0	60	0.01004	1.004	26,017			
	12.4	189	0.00953	1.063	25,829			
	12.3	682	0.00958	1.458	25,271			
	15.8	1090	0.01017	1.789	24,812			
2.4	16.2	1540	0.00996	2.177	24,513			
	17.2	2010	0.01026	2.470	24,257			
	18.9	3112	0.01024	3.103	23,893			
	17.8	3960	0.00992	3.615	23,666			
	14.4	5040	0.00972	4.130	23,351			

ternating magnetic force, or forces, into the interior of the conductor, thereby superposing a "spirality-effect"[6] upon the regular skin-effect of the same conductor unspiraled. These two effects are also capable of mutually modifying each other. The subject of "total skin-effect" in spiralled stranded conductors is therefore more complicated than that presented in

5. Pender, Bibliography No. 101.
6. Stirnimann, Bibliography No. 52, and Alfred Hay, No. 70.

unspiralled stranded or in solid conductors. It is proposed to carry further investigation into this question. Up to the present time, the seven-strand spiralled conductors tested, have shown practically the same skin-effect resistance ratios as equisectional solid wires, up to say 1200 ~; while between 1200 and 5000 ~, the ratio for the spiralled strands has been slightly greater than that of the solid wires, indicating in these instances, therefore, an added spirality effect. It may be mentioned that both the spirality effect and the skin effect of a subdivided conductor may be substantially annulled by insulating its strands and so transposing them that any one strand occupies, in succession, different positions in the cross-section.

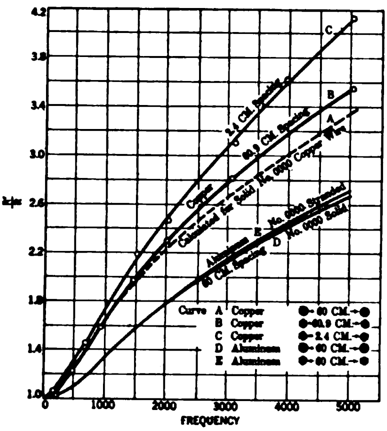


FIG. 9—SEVEN-STRAND CABLE—EQUIVALENT NO 0000 SOLID WIRE

Change of resistance with frequency for different spacing of conductors.

Table VI shows, in its last column, that the total loop inductance of the loop of stranded wire appeared to be about 0.983 per cent, or 1.7 per cent less than, the inductance of an equi-sectional solid wire at the same spacing and frequency as calculated by formula (*D* Table II.) This result is in substantial conformity with the deductions of Mr. H. B. Dwight[7], which are to the effect that a loop of two parallel unspiralled seven-strand conductors has 1.3 per cent less linear inductance than the equisectional solid conductors, all other conditions remaining unchanged. The change is attributable to the geometry of the loop system, and is independent of skin effect.

Aluminum Stranded Conductor. The results obtained on two loops of aluminum conductor, one of solid wires, No. 0000 A.W.G. (diameter 0.46 inch 1.168 cm. cross section 211,600 cir. mils 1.072 sq.cm.) and the other of seven-equal-strand conductors, of very nearly equal total cross-section (1.074 sq. cm. 211,950 cir. mils), are given in Fig. 9. It will be seen that the skin-effect resistance ratio of the stranded conductor, which

7. Bibliography No. 90.

had a lay of 23 cm., is slightly greater than that of the solid conductor above 2000 ~, and at 60 cm. spacing.

Strip Conductors. It is generally accepted among electrical engineers, that the skin-effect resistance ratio of flat strip conductors is less than that of equisectional solid round conductors. This proposition has been verified in the tests here reported, except at frequencies below 1000 ~, in which a higher skin-effect has been observed, in certain copper strips, than is obtained, by calculation, for equisectional round copper wires.

TABLE VII.—SKIN EFFECT IN COPPER STRIPS WITH 60-CM. SPACING BETWEEN CONDUCTORS

Strip size cm.	Temperature deg. cent.	Frequency cycles per sec.	R, d-c. resistance, ohms	$\frac{R'}{R}$	L, total abhenrys
1.26 × 0.1575	+6.8	225	0.0563	1.004	71,291
	−2.0	708	0.0539	1.038	71,147
	−1.8	1188	0.0541	1.085	70,970
	+6.0	1900	0.0554	1.161	70,679
	−1.5	2980	0.0541	1.261	70,383
	−5.0	3690	0.0534	1.326	70,247
	−1.3	5169	0.0543	1.426	68,765
2.52 × 0.158	+0.9	491	0.0260	1.065	60,482
	0.5	1022	0.0259	1.169	60,083
	0.1	2007	0.0259	1.314	59,699
	0.2	3078	0.0259	1.430	59,512
	0.0	3920	0.0259	1.506	59,402
	0.0	4980	0.0259	1.593	59,349
3.81 × 0.159	5.0	229	0.0173	1.042	55,576
	0.4	1136	0.0171	1.283	54,766
	5.0	1730	0.0173	1.363	54,586
	1.9	2645	0.0172	1.478	54,422
	5.2	3787	0.0174	1.588	54,303
	1.8	5050	0.0172	1.697	54,241

Three copper-strip conductors were employed in the different tests, each approximately 1/16 inch, (1.59 mm.) in thickness; namely, nominal ½-inch, 1-inch, and 1½-inch; actually 1.26 × 0.1575 cm., 2.52 × 0.158 cm. and 3.81 × 0.159 cm. One strip at a time was supported by vertical slits in wooden blocks, to form a straight loop, with parallel sides at the proper separating distance. Commencing with 60-cm. spacing, it was found to make no appreciable difference whether the strips forming the loop were in the same horizontal, or in parallel vertical

planes. When, however, the separating distance was about 10 cm., the relative setting of the two strips began to make a difference in the results, owing to proximity effects. This difference became very large when the separating distance was reduced to about one mm.

Table VII gives the results of the observations for the above mentioned sizes of strip, at the separating distance of approximately 60 cm. It will be seen that the skin-effect resistance ratio of the narrowest strip was only 1.0043 at 225 $\sim$; so that no attempt was made to measure this ratio at 60 $\sim$. The records in the table are plotted in the curves of Fig. 10, at A, B and C respectively, Curve D, which is slightly concave upwards, represents the corresponding computed ratio for infinitely wide copper strip, by formula (**103**).

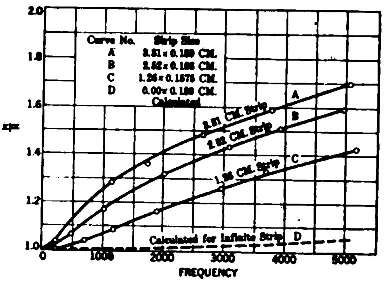


FIG. 10—COPPER STRIPS SPACED 60 CM.

Change of resistance with frequency for different width strips.

It is evident that at 60 cm. spacing, which is practically equivalent to infinite spacing, the calculated resistance ratio R'/R is very much less than the observed ratio, particularly at the higher frequencies. Moreover, it might be supposed at first thought, that a strip nearly 4 cm. wide, would approach the behavior of an infinitely wide strip more closely than a strip 1.26 cm. wide; whereas the reverse was the case, in these observations. The large deviations from theory here presented, at first threw some doubt on the measurements. These were, however, repeated, with substantially the same results, not only on the same bridge by different observers, and under different conditions at the Massachusetts Institute of Technology, Boston, but also upon another loop of the same strip, with entirely different measuring apparatus, at Pierce Hall, in Cambridge. There is at present no reason to doubt the results indicated in Fig. 10 outside the range of the usual small errors of observation. The authors have not been able to discover any published measurements of the skin effect in linear lat strips, at any spacing.

The reason for the large discrepancies between the theory for infinite strips, and the observations for strips of one to four

cm. width, is believed to be that the alternating magnetic flux surrounding the active strips, being more or less cylindrical in distribution, cuts through the substance of the strip to a greater or less extent, and in so doing dissipates power by eddy currents. Only in the case of extremely wide strips, may the alternating magnetic flux be properly regarded as lying in planes parallel to the surfaces of the strip, so as not appreciably to intersect therewith. There are two experimental evidences for this belief; namely (1) the distribution of magnetic flux paths around the active strips, as obtained by the method of scattering iron filings and (2) the fact that with the parallel strips brought close together, the skin effect was much greater when they lay in one and the same plane, than when they were supported in parallel planes.

Fig. 11 shows the magnetic flux distribution around a 2.5-cm. strip, 1.6 mm. thick, when carrying 107 amperes at 838 $\sim$, the return conductor being remote. It is evident that a considerable amount of this flux cuts the substance of the strip near the edges; so that it is not surprising that the extra power loss due to eddy currents in the strip should markedly increase the skin-effect.

Fig. 12 shows that when the two parallel strips forming the loop are placed in the same plane, edge to edge, and nearly touching, with 120 amperes at 858 $\sim$, practically all the magnetic flux threading through the loop has to cut some portion of the strip. We might, therefore, reasonably expect a relatively large excess loss of power by eddy currents in such a case, as observation actually showed.

Fig. 13 shows on the other hand, that when the two parallel strips forming the loop are placed in parallel planes, and separated only by a strip of paper, the alternating magnetic flux, with 120 amperes and 858 $\sim$, was very feeble. We should, therefore, expect to find comparatively little excess loss of power by eddy currents under such conditions, as actual observation revealed.

The results for the 2.5-cm. strips, at different spacings and relative positions, are given in Fig. 14. It will be seen that the smallest skin-effect ratio is with the shortest spacing (0.5 mm.) and with the strips in parallel planes as in Fig. 13. This is the result nearest to that given by the theory for infinitely wide strips. On the other hand, the largest ratio is at nearly the same spacing (one mm.), but with the strips lying in one and

the same plane as in Fig. 12. Between these extreme limits, lie all the other series, at least within the range of 0 to 4000 ~. The curve belonging to the series with 0.5-mm. spacing bends upwards, whereas all the others bend downwards beyond 500 ~. This appears to be related to the distributions of alternating magnetic fields. The theoretical curve also bends upwards. The broken line gives the ratios for a circular wire of the same cross-section as the strip, and at large spacing.

Corresponding results for the 3.8-cm. strips are indicated in Fig. 15. Here again, the difference is very marked between

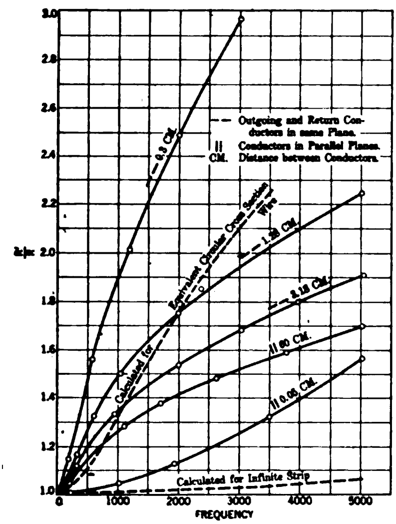


Fig. 14—Copper Strip 2.52 by 0.158 cm.

Change of resistance with frequency for different spacing of conductors.

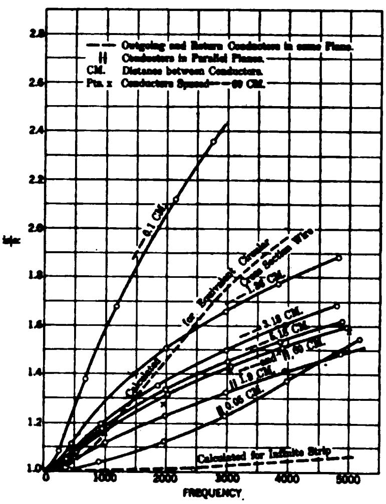


Fig. 15—Copper Strip 3.81 by 0.159 cm.

Change of resistance with frequency for different spacing of conductors.

the ratios for the smallest spacings 3 mm. and 0.5 mm., in the same and in parallel planes respectively, due to proximity effects. At 4000 ~, the former is about 3.4 and the latter 1.4; while the theoretical value for infinite strip of the same thickness is about 1.04.

The results concerning the total loop inductances for the 3.8 cm. strip, at different spacings and settings, are given graphically in Fig. 16. It will be seen that not only is the total inductance a minimum for the case of parallel spacing at 0.5 mm., but also the change of inductance with frequency; whereas

the greatest change of inductance with frequency is in the case of 3-mm. spacing in the same plane. The broken line gives the ratio for an equisectional circular rod at large spacing.

It is evident from the foregoing results that in the case of parallel flat strips, the proximity effects are very variable, may be relatively large, and depend in large measure upon the relative disposition of the two conductors.

It is open to discussion whether the proximity effect in such conductors is materially affected by the current strength in

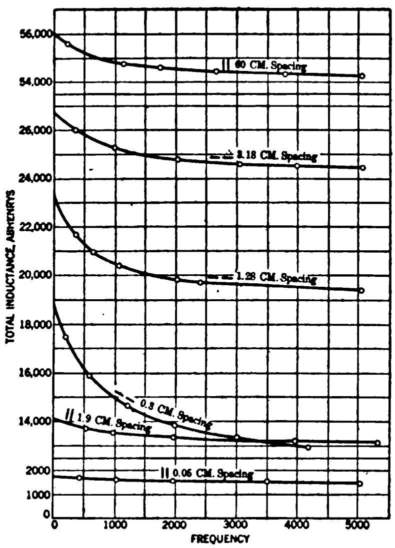


FIG. 16—COPPER STRIP 3.81 BY 0.159 CM.

Change of inductance with frequency for different spacing and positions of conductors.

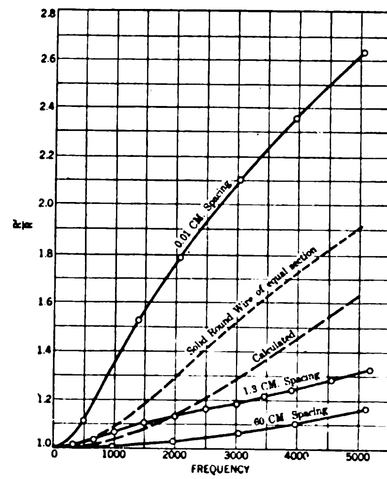


FIG. 17—WHOLE COPPER TUBE—OUTSIDE DIAMETER 1.266 CM., WALLS 0.159 CM.

Change of resistance with frequency for different spacing of conductors.

the loops. Between the limits of about 0.1 ampere and 3.0 amperes in the loops, at any frequency within the reported range, no change in the impedance ratio with current was observable.

TUBULAR CONDUCTORS

In order to measure skin effect in copper tubes, 90 feet (27.4 m.) of hard copper tube was obtained, ½ inch in external diameter (1.26 cm.) with 1/16 inch wall (1.6 mm.) in selected 15-foot length (4.56 m), and supported on insulators in a rec-

tangular loop, like the other conductors. The tubes were jointed by means of thin sleeves of copper, soldered over the ends. The loop had square ends, and was 13.1 m. long. Tests were made at three spacings between parallel tubes, namely, 60 cm., 1.3 cm., 0.1 mm. The results of these tests are given in the accompanying Table No. VIII and Fig. 17. It will be observed that at 60-cm. spacing, where the proximity effect is

TABLE VIII.—SKIN EFFECT IN A COPPER TUBE.

1.266 CM. OUTSIDE DIAMETER 0.159 CM. WALL.

Spacing cm.	Temperature deg. cent.	Frequency cycles per sec.	R, d-c. resistance, ohms	$\frac{R'}{R}$	L, total abhenrys
60.	4.2	222	0.01636	1.0004	25,125
	6.0	385	0.01626	1.0015	25,143
	4.8	963	0.01634	1.0088	25,121
	5.4	1967	0.01637	1.0298	25,108
	5.9	3030	0.01647	1.0633	25,109
	5.8	3962	0.01646	1.1046	25,098
	5.2	5120	0.01635	1.167	25,053
1.3	7.5	320	0.01580	1.013	7,583
	7.4	994	0.01580	1.067	7,461
	7.7	1987	0.01580	1.132	7,361
	7.5	3004	0.01578	1.188	7,311
	6.2	3915	0.01575	1.241	7,285
	5.5	5180	0.01572	1.327	7,090
	−0.2	4540	0.01559	1.288	7,279
	−0.1	3467	0.01559	1.216	7,303
	0.0	2482	0.01559	1.160	7,343
	0.0	1482	0.01560	1.102	7,405
	0.7	658	0.01561	1.039	7,519
0.01	8.3	488	0.01532	1.114	3,443
	8.7	1384	0.01530	1.524	2,825
	8.8	2040	.01530	1.787	2,543
	8.6	3030	0.01530	2.104	2,258
	8.8	3930	0.01528	2.364	2,079
	8.7	5040	0.01526	2.630	1,950

negligible, the skin-effect resistance-ratios are all relatively small, and much lower than those of other types of conductor tested in this research. With the spacing of only 0.1 mm.; *i.e.* with the tubes lashed side by side, and separated only by a thin strip of paper, the proximity effect was very marked, and was also sensitive to changes in the temperature of the surrounding air.

The theory of tubular conductors remote from disturbing

magnetic fields, has been given by Heaviside[8] and by Russell.[9] It involves Bessel functions of both the first and second kinds, and is complicated relatively to that of solid wires. The formulas developed for resistance-ratio are relatively lengthy and are only approximations. A much simpler approximate resistance-ratio formula for engineering purposes, is obtained by considering a tube as the equivalent of a strip with no disturbance at edges; *i.e.* behaving like a strip of infinite width. Strictly speaking, the curvature of the tubular conductor prevents the rigid application of the flat-strip theory; so that this theory can only be expected to apply to tubes of thin wall and large diameter. The formula for the resistance ratio of a flat strip is given in (**103**) of the Appendix. The full wall thickness of the tube is here regarded as corresponding to X the half-strip thickness.[10] Applying this formula to the case considered, we obtain the broken line marked "Calculated" in Fig. 17. It will be seen that the calculated ratios are all much larger than the observed ratios; although the shapes of the two curves considered, are similar. It was found, however, that if instead of taking the full wall thickness 0.16 cm. for X, we take two thirds of that thickness in the formula, *i.e.* $X =$ 0.106 cm., the resistance ratio thus calculated agrees satisfactorily with the observed values over the entire range of frequency investigated. It is not, however, apparent why only two-thirds of the wall thickness should be included in the formula, and perhaps this fraction applies only to the particular size of tube employed; so that this must be regarded as an empirical rule for the present.

Slotted Tube. Seeing that the resistance ratios for copper tubes were less than those offered by flat-strip theory; whereas actual narrow copper strips gave ratios in excess of that theory, it was decided to follow the behavior of the tubes as they were mechanically altered towards the form of flat strips. The first step in this mechanical transformation was to cut a single slot 0.02 inch wide (0.5 mm.) along the entire length on one side of the tube. The slotted tubes were then rejointed and supported in a long rectangular loop of the same length as before (13.1 m.), and the tests repeated for two spacings; namely, 60 cm. and 0.1 mm. In the latter case, two tests were made, one

8. Bibliography No. 2.
9. Bibliography No. 51.
10. Pender, Bibliography No. 101.

with the slots turned in, and the other with the slots out; *i.e.* with the slots at their minimum and maximum permissible distances apart, respectively. It was found that, at 60 cm., there was no perceptible change from the previous test at that spacing. That is, the skin-effect impedance-ratio of the tube, remote from disturbing a-c. magnetic fields, was as nearly as could be determined the same, whether the tube was complete, or had a thin slot cut in it longitudinally. At the 0.1-mm. spacing, however, the resistance ratio appeared to be distinctly less than in the unslotted condition; but seeing that the loop had to be taken down, reassembled and reerected between the two tests, with perhaps somewhat different mechanical pressures on the separating paper strip, in the two cases, it is considered unsafe to rely upon the deduction that slotting a tube reduces its proximity effect, as is apparently indicated in Fig. 18. There was no appreciable difference between the results in the two tests at 0.1 mm., with the slots turned inwards and outwards respectively.

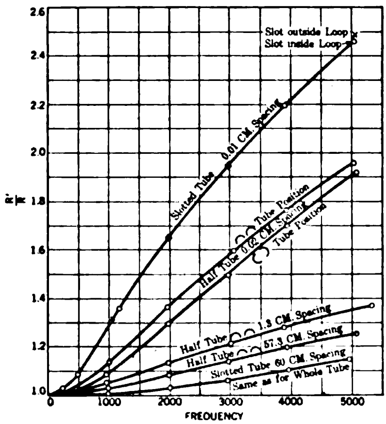


FIG. 18—SLOTTED and HALF COPPER TUBES—OUTSIDE DIAMETER 1.266 CM., WALLS 0.159 CM., SLOT 0.0508 CM.

Change of resistance with frequency for different spacing and positions of conductors.

Half Tubes. The loop of slotted tube was again disassembled, and the conductor split into two half tubes, by cutting a new horizontal slot on the opposite side to the first. The half-tubes were then jointed together to form a rectangular loop 13.1 m. long. This half-tube conductor loop was then tested at three spacings; namely, 57.3 cm., 1.3 cm. and 0.2 mm. The results of these tests are indicated in Fig. 18. It will be observed that at 57.3 cm., with negligible proximity effect, the resistance ratios are markedly higher than with whole tubes. At 1.3 cm., with the half tubes placed as though lying inverted, side by side, on a table, the resistance ratios were distinctly, although not greatly, increased by proximity effect. At the 0.2 mm. spacing, two tests were made, *i.e.* one with the half-tubes placed opposite each other, as though to form the original

tube, and the other as in the test at 1.3-cm. spacing. The former condition had a lower proximity effect than the latter, at least as far as 5000 ~, as indicated in Fig. 18.

Summing up, therefore, the results with tubes and half tubes, it may be stated that the skin-effect of tubes is much less than that of other forms of equisectional conductor. When the tube is cut into longitudinal halves, and one of the halves is removed, the skin-effect of the remaining half tube is considerably increased, and approaches, but is always less than, that of an equisectional flat strip.

In conclusion, we desire to express our acknowledgments to Prof. Harold Pender for his valuable contribution to the earlier stages of this research, both in design and in direction; also to Prof. D. C. Jackson for valuable suggestions during the progress of the work, also to the thesis work of Messrs. F. H. Achard, and H. E. Randall in 1912-1913, on the preliminary work. We are also indebted to Dr. S. B. Jewett for help in procuring special apparatus, and to Dr. E. B. Rosa of the Bureau of Standards, for the courteous loan of inductance standards.

Conclusions

1. The skin effect impedance-ratio of solid round wires of copper and aluminum, have been found to be in close accordance with the Bessel-function Heaviside-Kelvin theory, up to the highest frequency used in the tests (5000 ~).

2. At frequencies below 100 ~, the *proximity effect* is relatively small. That is, the close proximity of the going and returning parallel conductors does not greatly increase the skin effect. At higher frequencies, however, the proximity effect becomes very marked. All the forms of conductors tested developed marked proximity effects, near the higher frequencies, when brought close together. The proximity effect was usually imperceptible at separating distances above say 20 cm.

3. Stranded copper or aluminum conductors, without twists, appear to have the same skin-effect impedance-ratio as their equisectional solid conductors. Twisting and spiraling the strands, introduces a change in the ratio, called the *spirality effect.* In the very few cases of stranded conductors, thus far tested, the spirality effect added slightly to the skin effect.

4. Flat copper strips possess a much larger skin-effect resistance-ratio than corresponds to the theory for indefinitely wide strips. The discrepancy has shown itself to be due to the eddy-

current losses from the alternating magnetic flux linked with the strips, and intersecting them, especially near their edges. The proximity effect in strips is large near the higher frequencies, and is considerably affected by the relative positions of the going and returning strip-conductors.

5. Copper tubes have less skin effect than equisectional conductors of any other form tried. In the single size tested, the skin effect was that corresponding to indefinitely wide strip of thickness 33 per cent greater than that of the tube wall.

6. Half tubes, prepared by slitting a copper tube, have much more skin effect than the whole tube from which they are made. They have however less skin effect than flat strips of the same thickness and cross-section.

7. To reduce skin-effect in a pair of straight parallel single-phase conductors at frequencies up to 5000 $\sim$, the tests have corroborated the existing belief that the conductors should be tubular, or hollow cylinders, separated by more than 20 cm. On the other hand, to obtain the maximum current-distortion effect, solid rods of large diameter should be used, in close mutual proximity. Copper strips while showing, in most cases, less skin effect than equisectional solid rods, have much more skin effect than is generally supposed.

APPENDIX I

Theory of Conditions for Balance on the Heaviside Bridge

With the arrangement shown in Figs. 1 and 2, a shifting of the balance point, d, to the left, transfers resistance from the arm X to the arm P. At the same time, a certain amount of inductance in the slide wire, and in the mutual induction between the slide-wire and the detector circuit is also transferred.

To obtain R and L, the resistance and the inductance of the loop under test:

let r = the resistance per centimeter of the slide wire (ohms per cm.)

μ = twice the inductance change per centimeter of the slide wire, due to the change in position of the slider (henrys per cm.)

k = twice the resistance per unit length of the slide wire (ohms per cm.)

L_P' = the inductance of the arm P, excluding the slide wire (henrys.)

L_X' = the inductance of the arm X, excluding the slide wire and the inductance L_X (henrys.)

L_X = inductance of the experimental line to be determined. (henrys).

R_X = resistance of the experimental line, to be determined (ohms).

m_0 = mutual inductance necessary to balance bridge, when the line is short-circuited (henrys).

m_1 = mutual inductance necessary to balance bridge when the line is in circuit (henrys).

K = twice the mutual inductance per turn of the secondary winding (henrys per turn).

$n_0 - n_1$ = change in the number of turns on the secondary of the mutual inductance, which is necessary to restore balance when the short circuit is removed.

R_P' = resistance of the arm P, excluding the slide wire (ohms)

R_X' = resistance of the arm X excluding the slide wire and the resistance R_X (ohms).

l_0 = reading of slide wire when the line is short-circuited (cm.).

l_1 = reading of slide wire when the line is in circuit (cm.),

l = total length of slide wire (cm.)

By (**7**) from the first balancing

$$R_P' + l_0 r = R_X' + (l - l_0) r \qquad \text{ohms} \quad \textbf{(9)}$$

from the second balancing

$$R_P' + l_1 r = R_X' + (l - l_1) r + R_X \qquad \text{ohms} \quad \textbf{(10)}$$

$$\therefore R_X = 2r(l_1 - l_0) \qquad \text{“} \quad \textbf{(11)}$$

$$\text{or} \quad R_X = k(l_1 - l_0) \qquad \text{“} \quad \textbf{(12)}$$

By (**8**), from the first balancing

$$L_P' + \frac{\mu l_0}{2} = L_X' + \frac{\mu}{2}(l - l_0) + 2m_0 \qquad \text{henrys} \quad \textbf{(13)}$$

from the second balancing

$$L_P' + \frac{\mu l_1}{2} = L_X' + \frac{\mu}{2}(l - l_1) + 2m_1 + L_X \qquad \text{henrys} \quad \textbf{(14)}$$

$$L_X = 2(m_0 - m_1) + \mu(l_1 - l_0) \qquad \text{“} \quad \textbf{(15)}$$

$$\text{and} \quad L_X = K(n_0 - n_1) + \mu(l_1 - l_0) \qquad \text{“} \quad \textbf{(16)}$$

The working formulas are therefore (**12**) and (**16**).

APPENDIX II

THEORY OF SKIN EFFECT IN SOLID CYLINDRICAL UNIFORM CONDUCTORS WITH REMOTE RETURN

This theory was originally developed by Clerk Maxwell in 1873, and has, under certain variations of detail, been given by a number of writers since that date, as an examination of the references mentioned in the Bibliography will reveal. The essential steps of the reasoning are, however, repeated here; because the final solutions offered are believed to have certain advantages for engineering computations.

In Fig. 19, let $A\ B\ C$ be the cross-section of a uniform straight cylindrical conductor of radius X cm. with axis at 0, and surrounded by air, oil, or other non-magnetic dielectric. Let the

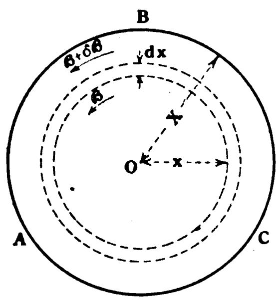


Fig. 19

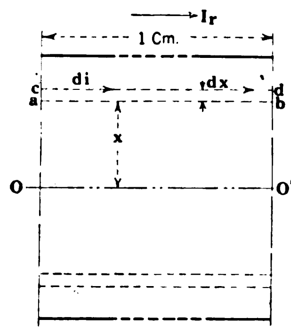


FIG. 20

wire be supposed to carry a sinusoidal alternating current I_r, r.m.s. absamperes[11], and to be so far remote from the parallel return conductor, that the magnetic field from the latter is insignificant at the region occupied by $A\ B\ C$. Then the external alternating magnetic field of this conductor $A\ B\ C$ will be just the same in magnitude and phase as the alternating current I_r would produce if there were no skin effect. That is, the skin effect is confined within the radius X. It affects the magnitudes and phases of the electric and magnetic fluxes within the conductor; but we may assume that (1), by symmetry, these fluxes are symmetrically distributed with respect to the axis O; so that if either the magnetic flux-density, or the current density, has a given instantaneous value at some radius x; then the same value will be developed, at that instant, at all points whose radius is x; (2)

11. The prefix ab- or abs- indicates a C.G.S. magnetic unit.

that there is at no time during the steady state, a radial component of electric or magnetic flux, that is, all fluxes are either parallel to the axis, or in cylindrical lines around the axis. By the "steady state" is meant the alternating-current state which is finally reached after the application of impressed alternating voltage in the circuit.

Let i_x = the instantaneous current density at radius x (absamperes per sq. cm.).

$\mathcal{H}_x$ = the magnetic intensity at radius x (gilberts per cm.)

$\mathcal{B}_x$ = magnetic flux density at radius x (gausses).

γ = the conductivity of the material in the conductor (abmhos per cm.).

ρ = $1/\gamma$ the resistivity (absohm-cm).

μ = the permeability $\left(\frac{\text{gausses}}{\text{gilberts per cm.}}\right)$

f = the frequency of the impressed alternating current (cycles per second).

ω = $2\pi f$, the angular velocity (radians per second).

η_x = $\eta_{mx} - \epsilon^{j\omega t}$ the electric alternating intensity externally impressed on the conductor $\left(\frac{\text{abvolts}}{\text{linear cm.}}\right)$

j = $\sqrt{-1}$

ϵ = 2.71828 . . . the Napierian base.

Then, if we integrate the magnetic intensity $\mathcal{H}_x$ around the circle of radius x, we obtain $2\pi x\,\mathcal{H}_x$ gilberts, and this must be equal to 4π times the total vector current strength within this circle; that is

$$2\pi x \mathcal{H}_x = 4\pi \int_0^x 2\pi x \,.\, i_x \,.\, dx \qquad \text{absamperes} \angle \quad (17)$$

or

$$\frac{d\,(x\,.\,\mathcal{H}_x)}{dx} = 4\pi\, x\,.\,i_x \qquad \text{“} \quad \text{“} \quad (18)$$

and

$$i_x = \frac{1}{4\pi}\left(\frac{\mathcal{H}_x}{x} + \frac{d\mathcal{H}_x}{dx}\right) \qquad \frac{\text{absamperes}}{\text{sq. cm.}} \angle \quad (19)$$

If we take one cm. length of the conductor, as indicated in Fig. 20, and suppose that, at radius x, the current density directed from 0 to 0′ is rising at the instant considered; then magnetic

flux will be entering the rectangle $a\ b\ c\ d$ towards the observer at the rate $\mu \cdot x\, d \cdot \frac{d\mathcal{H}_x}{dt}$ maxwells per second, and generating a momentary e.m.f. of this numerical value around this rectangle, in the direction of the arrows. In order that there shall be no radial component of current flow in this rectangle, the total e.m.f. around this rectangle must be zero. The electric intensity η_x, or the e.m.f. in the centimeter ab will be $\rho\, i_x$ abvolts, directed with the current, or from a to b. Similarly, the electric intensity in dc will be $\rho \left(i_x + \frac{di_x}{dx} \cdot dx \right)$, directed from c to d. The total e.m.f. in the rectangle is then by Ohm's law,

$$\mu \cdot dx \cdot \frac{d\mathcal{H}_x}{dt} - \frac{di_x}{d_x} \cdot dx \cdot \rho = 0 \qquad \text{abvolts} \angle \quad (\mathbf{20})$$

or
$$\rho \frac{di_x}{dx} = \mu \frac{d\mathcal{H}_x}{dt} \qquad \frac{\text{abvolts}}{\text{radial cm.}} \angle \quad (\mathbf{21})$$

Differentiating (**19**) with respect to time, we obtain

$$\frac{di_x}{dt} = \frac{1}{4\pi} \left(\frac{d^2\mathcal{H}_x}{dx \cdot dt} + \frac{1}{x} \frac{d\mathcal{H}_x}{dt} \right) \qquad \frac{\text{absamperes}}{\text{sq. cm. sec.}} \angle \quad (\mathbf{22})$$

Substituting (**21**)

$$\frac{di_x}{dt} = \frac{\rho}{4\pi\mu} \left(\frac{d^2 i_x}{d_x^2} + \frac{1}{x} \frac{di_x}{dx} \right) \qquad \frac{\text{absamperes}}{\text{sq. cm. sec.}} \angle \quad (\mathbf{23})$$

or

$$\frac{d^2 i_x}{d_x^2} + \frac{1}{x} \frac{di_x}{dx} = \frac{4\pi\mu}{\rho} \cdot \frac{di_x}{dt} = 4\pi\gamma\mu \cdot \frac{di_x}{dt} \qquad \frac{\text{absamperes}}{\text{cm.}^4} \angle \, (\mathbf{24})$$

But i_x is varying sinusoidally, at any radius; so that

$$\frac{di_x}{dt} = j\,\omega\, i_x \qquad \frac{\text{absamperes}}{\text{sec. cm.}^2} \angle \quad (\mathbf{25})$$

and

$$\frac{d^2 i_x}{dx^2} + \frac{1}{x}\frac{di_x}{dx} + (-j\,4\,\pi\,\gamma\,\mu\,\omega)\,i_2 = 0 \quad \frac{\text{absamperes}}{\text{cm.}^4} \angle \quad \textbf{(26)}$$

If we denote $(-j\,4\,\pi\,\gamma\,\mu\,\omega)$ by $\alpha_0{}^2$ $\quad \frac{1}{\text{cm.}^2} \angle$ **(27)**

then

$$\frac{d^2 i_x}{dx^2} + \frac{1}{x}\frac{di_x}{dx} + \alpha_0{}^2\, i_x = 0 \quad \frac{\text{absamperes}}{\text{cm.}^4} \angle \quad \textbf{(28)}$$

This is a well known typical form of second-order Bessel differential equation, whose solution may conveniently be expressed in Bessel functions

$$i_x = A \cdot J_0\,(\alpha_0 x) + B \cdot K_0\,(\alpha_0 x) \quad \frac{\text{absamperes}}{\text{cm.}^2} \angle \quad \textbf{(29)}$$

where $J_0\,(\alpha_0 x)$ is a zero-order Bessel function of x of the first kind, and $K_0\,(\alpha_0 x)$ is a zero-order Bessel function of x of the second kind, while A and B are arbitrary constants.

Similarly, differentiating (**19**) with respect to x, we have

$$\frac{di_x}{dx} = \frac{1}{4\pi}\left(\frac{1}{x}\frac{d\,\mathcal{H}_x}{dx} - \frac{\mathcal{H}_x}{x^2} + \frac{d^2\,\mathcal{H}_x}{dx^2}\right) \quad \frac{\text{absamperes}}{\text{cm.}^3} \angle \quad \textbf{(30)}$$

and substituting from (**21**)

$$\frac{d\,\mathcal{H}_x}{dt} = \frac{1}{4\,\pi\,\gamma\,\mu}\left(\frac{1}{x}\frac{d\mathcal{H}_x}{dx} - \frac{\mathcal{H}_x}{x^2} + \frac{d^2\,\mathcal{H}}{dx^2}\right) \quad \frac{\text{gilberts}}{\text{cm. sec.}} \angle \quad \textbf{(31)}$$

and remembering that $\mathcal{H}_x$ is a sinusoidal quantity of angular velocity ω,

$$j\,\omega\,\mathcal{H}_x = \frac{1}{4\,\pi\,\gamma\mu}\left(-\frac{\mathcal{H}_x}{x^2} + \frac{1}{x}\frac{d\mathcal{H}_x}{dx} + \frac{d^2\,\mathcal{H}_x}{dx^2}\right)$$

$$\frac{\text{gilberts}}{\text{cm.sec.}} \angle \quad \textbf{(32)}$$

or

$$\frac{J\,d^2\,\mathcal{H}_x}{dx^2} + \frac{1}{x}\frac{d\,\mathcal{H}_x}{dx} + \mathcal{H}_x\left(-j\,4\,\pi\,\gamma\,\mu\,\omega - \frac{1}{x^2}\right) = 0$$

$$\frac{\text{gilberts}}{\text{cm.}^3} \angle \quad \textbf{(33)}$$

$$\frac{d^2\mathcal{H}_x}{dx^2} + \frac{1}{x}\frac{d\,\mathcal{H}_x}{dx} + \mathcal{H}_x\left(\alpha_0{}^2 - \frac{1}{x^2}\right) = 0 \quad \frac{\text{gilberts}}{\text{cm.}^3} \angle \quad \textbf{(34)}$$

A typical Bessel differential equation of the second order, whose solution is

$$\mathcal{H}_x = A' \cdot J_1\ (\alpha_0 x) + B' \cdot K_1\ (\alpha_0 x) \qquad \frac{\text{gilberts}}{\text{cm}}\ \angle \quad \mathbf{(35)}$$

where $J_1\ (\alpha_0 x)$ is a first-order Bessel's function of x, of the first kind, and $K_1\ (\alpha_0 x)$ is a first-order Bessel's function of x, of the second kind. It can be shown that in order to comply with the physical conditions of the problems, both B and B' must vanish; so that we obtain

$$i_x = A \cdot J_0\ (\alpha_0 x) \qquad \frac{\text{absamperes}}{\text{sq. cm.}}\ \angle \quad \mathbf{(36)}$$

$$\mathcal{H}_x = A' \cdot J_1\ (\alpha_0 x) \qquad \frac{\text{gilberts}}{\text{cm.}}\ \angle \quad \mathbf{(37)}$$

where A and A' are constants determined by the particular conditions of each case, and α_0 is the " semi-imaginary " quantity $\alpha_2 - j\,\alpha_2$

$$\alpha_0 = \sqrt{2\pi\gamma\mu\omega} - j\sqrt{2\pi\gamma\mu\omega} = \sqrt{4\pi\gamma\mu\omega}\ \backslash 45^\circ \qquad \text{cm.}^{-1}\ \angle \quad \mathbf{(38)}$$

i. e., a complex quantity, whose real and imaginary components are equal. The current density i_x at radius x, is therefore a constant A times the zero-Bessel function of the semi-imaginary $\alpha_0 x$, and $\mathcal{H}_x$, the magnetic intensity at radius x, is a constant A' times the first-Bessel function of the same semi-imaginary. Similarly, the electric intensity at radius x is

$$\eta_x = A\ \rho \cdot J_0\ (\alpha_0 x) \qquad \frac{\text{abvolts}}{\text{cm.}}\ \angle \quad \mathbf{(39)}$$

and the magnetic flux-density at radius x is

$$B_x = A'\mu \cdot J_1\ (\alpha_0 x) \qquad \text{gausses}\ \angle \quad \mathbf{(40)}$$

If we take $x = X$, the radius of the conductor, we obtain from **(36)**

$$i_X = A \cdot J_0\ (\alpha_0 X) \qquad \frac{\text{absamperes}}{\text{sq. cm.}}\ \angle \quad \mathbf{(41)}$$

and dividing **(36)** by **(41)**

$$\frac{\eta_x}{\eta_X} = \frac{i_x}{i_X} = \frac{J_0\ (\alpha_0 x)}{J_0(\alpha_0 X)} \qquad \text{numeric}\ \angle \quad \mathbf{(42)}$$

Similarly

$$\frac{B_x}{B_z} = \frac{\mathcal{H}_x}{\mathcal{H}_z} = \frac{J_1(\alpha_0 x)}{J_1(\alpha_0 X)} \qquad \text{numeric} \angle \quad \textbf{(43)}$$

For the benefit of those who are not familiar with Bessel's functions, a few definitions may here be given. For any real quantity z,

$$J_0(z) = 1 - \frac{\left(\frac{z}{2}\right)^2}{1!\,1!} + \frac{\left(\frac{z}{2}\right)^4}{2!\,2!} - \frac{\left(\frac{z}{2}\right)^6}{3!\,3!} + \ldots\ldots \text{numeric} \qquad \textbf{(44)}$$

and

$$J_1(z) = \frac{z}{2}\left\{\frac{1}{1!} - \frac{\left(\frac{z}{2}\right)^2}{1!\,2!} + \frac{\left(\frac{z}{2}\right)^4}{2!\,3!} - \frac{\left(\frac{z}{2}\right)^6}{3!\,4!} + \ldots\ldots\right. \text{numeric} \qquad \textbf{(45)}$$

Similarly

$$J_p(z) = \sum_{n=0}^{n=\infty}\left(\frac{z}{2}\right)^p \left\{\frac{(-1)^n\left(\frac{z}{2}\right)^{2n}}{n!\,(p+n)!}\right\} \qquad \text{numeric} \quad \textbf{(46)}$$

If z is a complex quantity of the type $z/\underline{\delta}$, z being the modulus, and δ the argument,
Then

$$J_0(z/\underline{\delta}) = 1 - \frac{\left(\frac{z}{2}\right)^2 \angle 2\delta}{1!\,1!} + \frac{\left(\frac{z}{2}\right)^4 \angle 4\delta}{2!\,2!} - \frac{\left(\frac{z}{2}\right)^6 \angle 6\delta}{3!\,3!} \ldots\ldots \qquad \text{numeric} \angle \quad \textbf{(47)}$$

and

$$J_1(z/\underline{\delta}) = \frac{z}{2}/\underline{\delta}\left\{\frac{1}{1!} - \frac{\left(\frac{z}{2}\right)^2 \angle 2\delta}{1!\,2!}\right.$$

$$+ \frac{\left(\frac{z}{2}\right)^4 \angle 4\delta}{2!\,3!} - \frac{\left(\frac{z}{2}\right)^6 \angle 6\delta}{3!\,4!} + \ldots\ldots \text{numeric} \angle \quad \textbf{(48)}$$

Similarly

$$J_p(z/\underline{\delta}) = \sum_{n=0}^{n=\infty}\left(\frac{z}{2}\right)^p \angle p\delta \left\{\frac{(-1)^n\left(\frac{z}{2}\right)^{2n} \angle 2n\delta}{n!\,(p+n)!}\right\} \qquad \text{numeric} \angle \quad \textbf{(49)}$$

It is evident therefore that a Bessel's function of any complex quantity is an infinite ascending series of powers of that quantity, the coefficients being formed on a definite schedule, depending on the order of the function.

Turning now to (**43**), we know that if the total maximum cyclic vector current strength carried by the conductor is I_m absamperes, the maximum cyclic magnetic intensity $\mathcal{H}_x$ at the surface is

$$\mathcal{H}_{xm} = \frac{2\ I_m}{X} \qquad \frac{\text{gilberts}}{\text{cm.}} \quad \angle \quad (\mathbf{50})$$

in phase with the current I_m. If, however, we prefer to consider not the maximum cyclic, but the root-mean-square value of the total vector current

$$I_r = I_m \ / \ \sqrt{2} \qquad \text{r.m.s. absamperes} \ \angle \quad (\mathbf{51})$$

Then the corresponding r.m.s. value of the magnetic intensity at the surface is

$$\mathcal{H}_{xr} = \frac{2\ I_r}{X} \qquad \frac{\text{gilberts}}{\text{cm.}} \quad \angle \quad (\mathbf{52})$$

and the r.m.s. flux-density at the surface, to current phase as standard,

$$B_{xr} = \frac{2\ \mu\ I_r}{X} \qquad \text{gausses} \ \angle \quad (\mathbf{53})$$

Consequently, the r.m.s. value of the magnetic intensity $\mathcal{H}_{xr}$, at radius x cm, is by (**43**)

$$H_{xr} = \frac{2\ I_r\ J_1\ (\alpha_0 x)}{X\ J_1\ (\alpha_0 X)} \qquad \frac{\text{r.m.s. gilberts}}{\text{cm.}} \quad \angle \quad (\mathbf{54})$$

to current standard phase. Thus, if a copper rod 1 cm. in diameter ($X = 0.5$) has a resistivity of 1724 absohm-cm. ($\gamma = 1/(1724) = 0.580 \times 10^{-3}$), a permeability $\mu = 1$, and is traversed by a r.m.s. sinusoidal current of 20 amperes, ($I_r = 2$ absamperes) at a frequency of 786 cycles per second, ($\omega =$ 4938 radians/sec.) Then

$$\alpha_0 = \sqrt{-j\,12.57 \times 0.58 \times 10^{-3} \times 4.938 \times 10^{-3}}$$
$$= \sqrt{12.57 \times 0.58 \times 4.938 \ \overline{\backslash 90^\circ}}$$
$$= \sqrt{36.0 \ \overline{\backslash 90^\circ}} = 6.0 \ \overline{\backslash 45^\circ} \qquad \text{cm.}^{-1};$$

so that

$$\alpha_0 X = 3.0 \diagdown 45^\circ = 2.121 - j\, 2.121 \qquad \text{numeric} \angle \quad (55)$$

by appended Table IX of J_1 $(z \overline{\diagdown 45^\circ})$, we find J_1 $(3.0 \diagdown 45^\circ$ $= 1.8 \underline{/15.^\circ 714}$

Consequently,

$$\mathfrak{K}_{xr} = \frac{2 \times 2 \times J_1 (\alpha_0 x)}{0.5 \times 1.8 \underline{/15^\circ.714}} = 4.444 \overline{\diagdown 15^\circ.714} \,.\, J_1 (\alpha_0 x)$$

$$\frac{\text{r.m.s. gilberts}}{\text{cm}} \angle \quad (56)$$

At the axis of the wire or $x = 0$, $J_1 (0 \overline{\diagdown 45^\circ}) = 0 \diagdown 45^\circ$
and

$$\mathfrak{K}_{0r} = 0.0 \overline{\diagdown 60^\circ.714} \qquad \frac{\text{r.m.s. gilberts}}{\text{cm.}} \angle \quad (57)$$

or, the intensity is vanishingly small, lagging 60°.7 behind the total vector current; and also 60°.7 behind the intensity at the surface of the wire. At $x = 0.25$ cm., or half way down to the axis, $\alpha_0 x \mp 1.5 \diagdown 45^\circ$, and

$$\begin{aligned}\mathfrak{K}_{xr} &= 4.444 \overline{\diagdown 15^\circ.714} \,.\, J_1 \; (1.5 \overline{\diagdown 45^\circ}) \\ &= 4.444 \overline{\diagdown 15^\circ.714} \times 0.7599 \overline{\diagdown 28^\circ.952} \\ &= 3.577 \overline{\diagdown 44^\circ.666} \qquad \text{r.m.s. gilberts/cm.} \angle \quad (58)\end{aligned}$$

i. e., 0.447 of the full surface value. At the surface, $X = 0.5$ and $\mathfrak{K}_{xr} = 8 \underline{/0^\circ}$ r.m.s. gilberts per cm.

Next considering (**42**), we are usually unable to apply this formula directly; because we do not know the value of the electric intensity η_x at the surface, or the current density i_x which it produces. It becomes necessary, therefore, to find the average current density, taking skin effect into account. It is evident that the total vector r.m.s. current strength I_r (absamperes) in the wire, if i_{xr} is the r.m.s. current density at radius x, will be

$$I_r = \int_0^X 2\pi x \cdot i_{xr} \cdot dx = 2\pi \int_0^X x \cdot i_{xr} \cdot d_x$$

$$\text{r.m.s. absamperes} \angle \quad (59)$$

and dividing this by πX^2, the area of cross-section of the wire, we obtain the average vector r.m.s. current density $\dot{i}_{qr}$ in the presence of skin effect; namely

$$\dot{i}_{qr} = \frac{I_r}{\pi X^2} = \frac{2}{X^2} \int_0^X x \cdot \dot{i}_{xr} \, dx \cdot \qquad \frac{\text{r.m.s.absampere}}{\text{sq. cm.}} \angle \quad (60)$$

Substituting for i_{xr}, the value from (**42**) in terms of i_{Xr} we have

$$\dot{i}_{qr} = \frac{2}{X^2} \cdot \frac{i_{Xr}}{J_0(\alpha_0 X)} \cdot \int_0^X x \cdot J_0(\alpha_0 x) \cdot dx \qquad \frac{\text{r.m.s.absamperes}}{\text{sq. cm.}} \angle \quad (61)$$

It will be found that the integral of $mx/\underline{\delta}$ times the zero-Bessel function of a complex quantity $mx/\underline{\delta}$, with modulus mx and argument δ, is

$$\int mx/\underline{\delta} \cdot J_0(mx/\underline{\delta}) \cdot dx = x J_1(mx/\underline{\delta}) \qquad \text{numeric} \angle \quad (62)$$

Applying this integral, we obtain

$$\dot{i}_{qr} = \frac{2}{X^2} \cdot \frac{iX_r}{J_0(\alpha_0 X)} \cdot \frac{1}{\alpha_0} \int_0^X \alpha_0 x \cdot J_0(\alpha_0 x) \, . \, dx$$

$$= \frac{2}{X^2} \cdot \frac{iX_r}{J_0(\alpha_0 X)} \cdot \frac{1}{\alpha_0} \left[x \cdot J_1(\alpha_0 x) \right]_0^X$$

$$= \frac{2}{X^2} \cdot \frac{iX_r}{J_0(\alpha_0 X)} \cdot \frac{X}{\alpha_0} \cdot J_1(\alpha_0 X)$$

$$= \frac{2}{\alpha_0 X} \cdot iX_r \cdot \frac{J_1(\alpha_0 X)}{J_0(\alpha_0 X)} \qquad \frac{\text{r.m.s.absamperes}}{\text{sq. cm.}} \angle \quad (63)$$

whence

$$\frac{i_{xr}}{i_{qr}} = \frac{\alpha_0 X}{2} \cdot \frac{J_0(\alpha_0 x)}{J_1(\alpha_0 X)} \qquad \text{numeric} \angle \quad (64)$$

Thus at the axis, where $x = 0$, $\alpha_0 x = 0 \backslash 45°$, and $J_0(\alpha_0 x) = 1.0 \underline{/0°}$,

$$\frac{i_{0r}}{i_{qr}} = \frac{\alpha_0 X}{2} \cdot \frac{1}{J_1(\alpha_0 X)} \qquad \text{numeric } \angle \quad (65)$$

In the case above considered with $\alpha_0 X = 3.0 \overline{\backslash 45°}$,

$$\frac{i_{0r}}{i_{qr}} = \frac{1.5 \backslash 45°}{1.8 \underline{/15°.714}} = 0.8333 \overline{\backslash 60°.714} \qquad \text{numeric } \angle \quad (66)$$

or the axis r.m.s. current density is 83.33% of the average current density, as deduced from the actual r.m.s. current and the cross-section. At the surface, $J_0(\alpha_0 X) = J_0(3.0 \backslash 45°) = 1.9502 \underline{/96°.518}$; so that

$$\frac{iX_r}{i_{qr}} = 0.8333 \overline{\backslash 60°.714} \times 1.9502 \underline{/96.°518} = 1.625 \overline{\backslash 35°8.04} \qquad \text{numeric } \angle \quad (67)$$

or the surface density is 62.5% greater than the average density:

If we consider that the surface r.m.s. current density is equal to that which the same numerical continuous electric intensity would produce in the linear d-c. resistance R, whereas the average r.m.s. density is that which the r.m.s. a-c. electric intensity actually produces in the presence of the linear internal impedance $Z = R' + jX'$; it follows that

$$\frac{Z}{R} = \frac{iX_r}{i_{qr}} = \frac{\alpha_0 X}{2} \cdot \frac{J_0(\alpha_0 X)}{J_1(\alpha_0 X)} \qquad \text{numeric } \angle \quad (68)$$

Here $\frac{Z}{R}$ is the "skin-effect impedance ratio." The real component of this ratio is $\frac{R'}{R}$, the "skin-effect resistance ratio"; while the reactive component of this ratio is $\frac{jX'}{R}$ the "skin-effect reactance ratio."

Thus, in the case considered, by (**67**)

$$\frac{Z}{R} = 1.625 \underline{/35°.804} = 1.318 + j\,0.9507 \qquad \text{numeric } \angle \quad (69)$$

so that the skin-effect impedance ratio of the wire at this frequency is 1.625, its skin-effect resistance ratio 1.318, and its skin-effect reactance ratio 0.9507. The apparent a-c. resistance of the wire is therefore 31.8 per cent greater than the d-c. resistance.

If, therefore, we denote the skin-effect impedance ratio as obtained in (**68**) by the complex quantity $M\underline{/\beta^\circ}$, where $M = |Z/R|$, and $\beta^\circ = \underline{/Z/R}$,

$$\frac{Z}{R} = M\,\underline{/\beta^\circ} \qquad \text{numeric } \angle \quad (\mathbf{70})$$

then

$$\frac{R'}{R} = M \cos \beta \qquad \text{numeric} \quad (\mathbf{71})$$

and

$$\frac{X'}{R} = \frac{L'\omega}{R} = M \sin \beta \qquad \text{numeric} \quad (\mathbf{72})$$

But the internal linear inductance L of a round wire, in the absence of skin effect, is

$$L = \frac{\mu}{2} \qquad \frac{\text{abhenrys}}{\text{wire cm.}} \quad (\mathbf{73})$$

So that

$$\frac{L\omega}{R} = \frac{\mu\omega}{2R} = \frac{\mu\ \omega \cdot \pi\ X^2}{2}\gamma \qquad \text{numeric} \quad (\mathbf{74})$$

$$= \frac{4\ \pi\ \mu\ \gamma\ \omega\ X^2}{8} = \frac{|\alpha_0 X|^2}{8} \qquad \text{numeric} \quad (\mathbf{75})$$

$$\frac{L'}{L} = \frac{8\ M \sin \beta}{|\alpha_0 X|^2} \qquad \text{numeric} \quad (\mathbf{76})$$

where $|\alpha_0 X|$ denotes the modulus, or length factor, of the plane vector $\alpha_0 X$. In the case above considered, $|\alpha_0 X| = 3$, and

$$M \sin \beta = 09.507; \text{ so that } \frac{L'}{L} = \frac{8 \times 0.9507}{9} = 0.8456$$

The apparent linear internal inductance of the wire in the presence of skin-effect, is 84.56 per cent of that for zero frequency.

The radial skin thickness δ cm., which is equivalent, at full

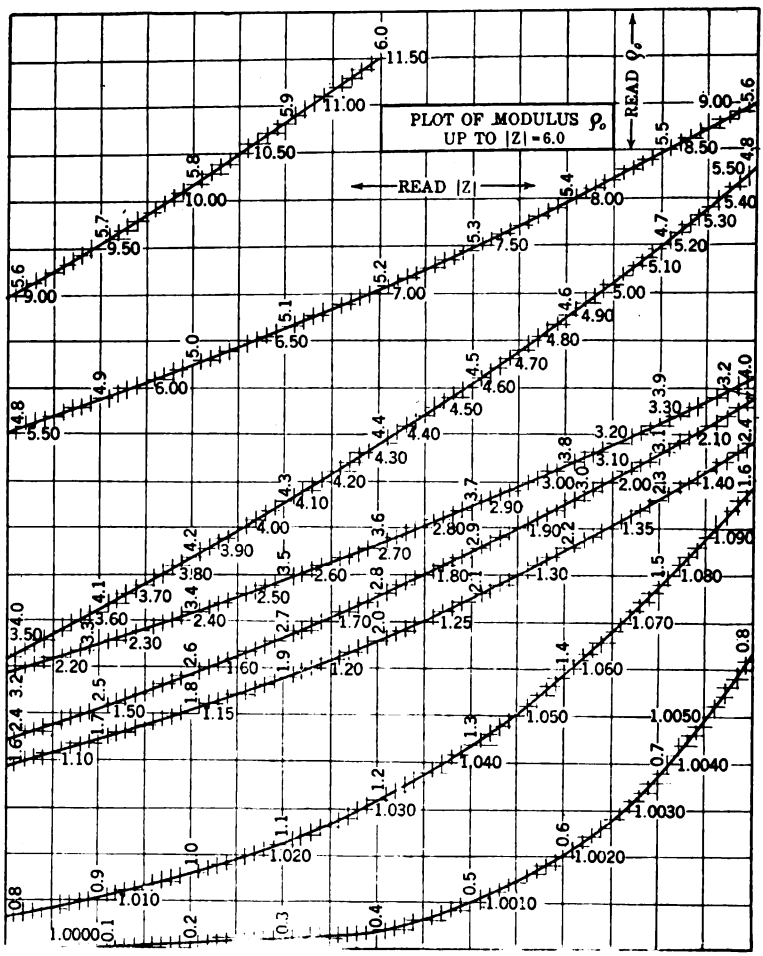


FIG. 21—INTERPOLATION CHART FOR BESSEL FUNCTIONS OF THE ZERO ORDER OF THE SEMI-IMAGINARY QUANTITY $Z\diagdown 45°$

$$J_0(\alpha_0 x) = J_0(x\sqrt{4\pi\gamma\mu\omega}\diagdown 45°) = J_0(z\diagdown 45°) = \rho_0 \angle \theta_0°$$

conductivity, to the actual wire at the average conductivity of skin effect, is given by

$$\delta = X\left(1 - \sqrt{1 - \frac{R}{R'}}\right) \qquad \text{cm.} \quad (76\ a)$$

In the case above considered $\delta = 0.2544$ cm.

Table IX gives the values of both $J_0\ (Z \backslash 45°)$ and $J_1\ (Z \backslash 45°)$, for the range $z = 0$ to $z = 10$, by steps of 0.1; while Figs. 21 to 24 give curves corresponding to the entries in the table, whereby

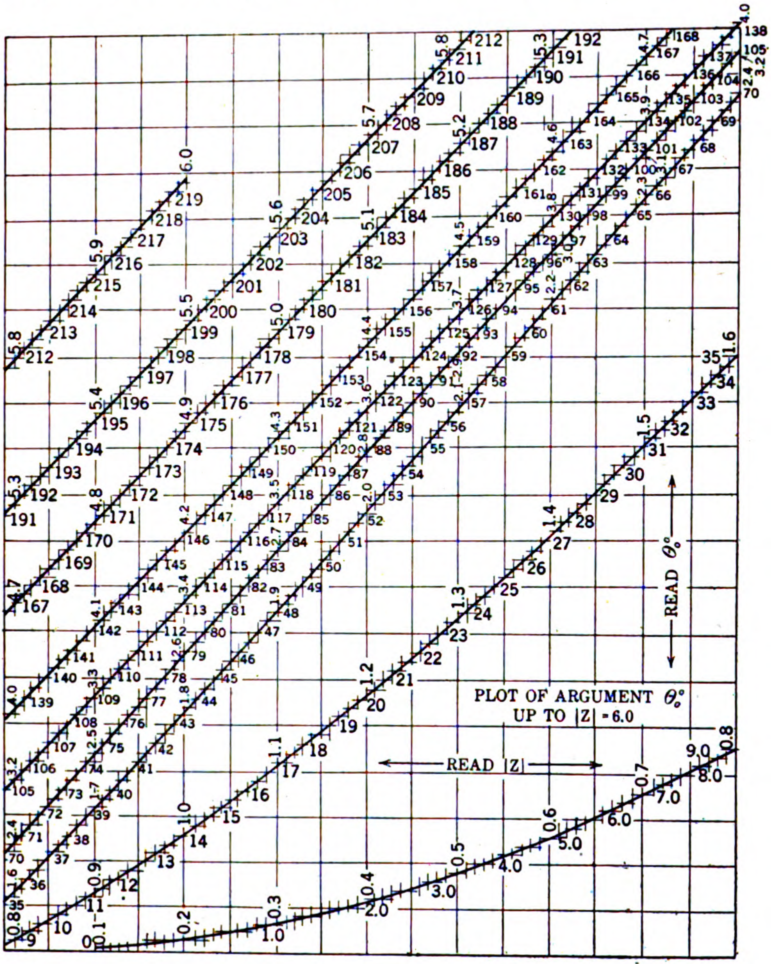


FIG. 22—INTERPOLATION CHART FOR BESSEL FUNCTIONS OF THE ZERO ORDER OF THE SEMI-IMAGINARY QUANTITY $Z \backslash 45°$

$$J_0\,(\alpha_0 x) = J_0\,(x \sqrt{4\,\pi\,\gamma\,\mu\,\omega} \backslash 45°) = J_0\,(z \backslash 45°) = \rho_0 \,\underline{/\,\theta_0}°$$

interpolation may be made, by direct inspection, for most engineering purposes. The curves in Fig. 21 give the modulus of $J_0\ (z \backslash 45°)$, in Fig. 22 the amplitude of the same function, in Fig. 23 the modulus of $J_1\ (z \backslash 45°)$, and in Fig. 24 the amplitude

of the same function. Table IX has been worked out from already-existing tables of ber-bei ber′-bei′ functions, using **(77)** and **(78)**. The polar form of the Bessel functions obtained from Table IX gives them distinct arithmetical advantages.

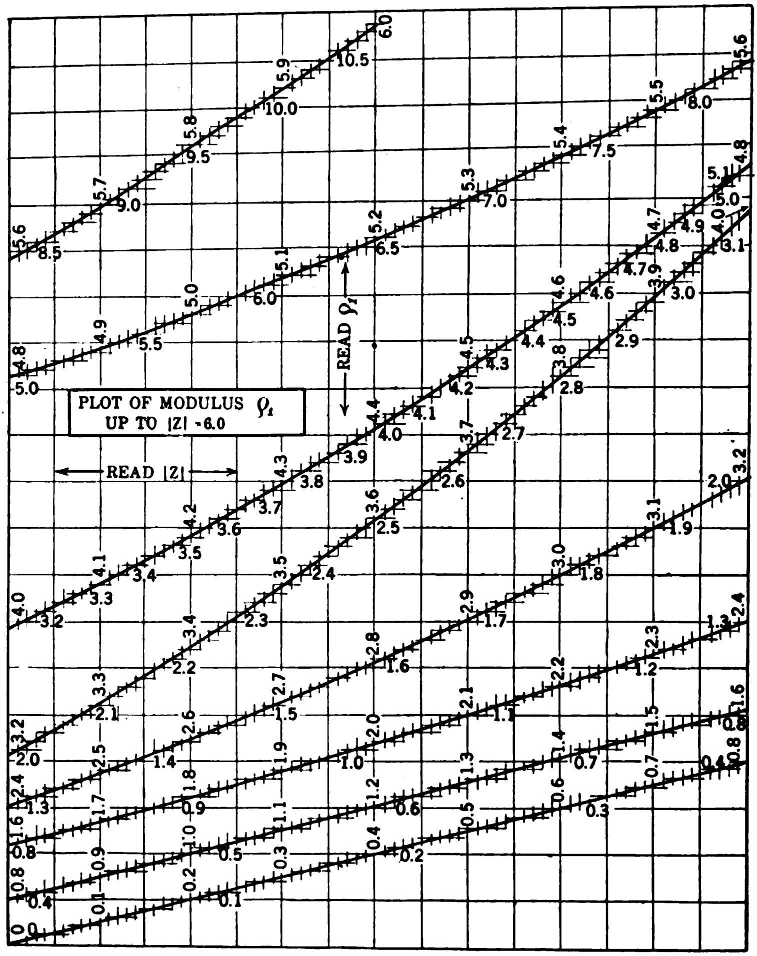


FIG. 23—INTERPOLATION CHART FOR BESSEL FUNCTIONS OF THE FIRST ORDER OF THE SEMI-IMAGINARY QUANTITY $Z\backslash 45°$

$$J_1(\alpha_0 x) = J_1 x\sqrt{4\pi\gamma\mu\omega}\backslash 45°) = J_1(z\backslash 45°) = \rho_1 \underline{/\theta_1°}$$

Table X gives the value of $|\alpha_0| = \sqrt{4\pi\gamma\mu\omega}$, the modulus of the propagation constant, for the case of round copper wires, of international standard conductivity at 20°C., for various values of impressed frequency up to 5000 ∼. By its use, in conjunction

with Table IX, the computation of the electric intensity η_x, the electric-current density i_x, the magnetic intensity $\mathcal{H}_x$, or flux density $\mathcal{B}_x$, at any radius x, in a round wire, is facilitated through

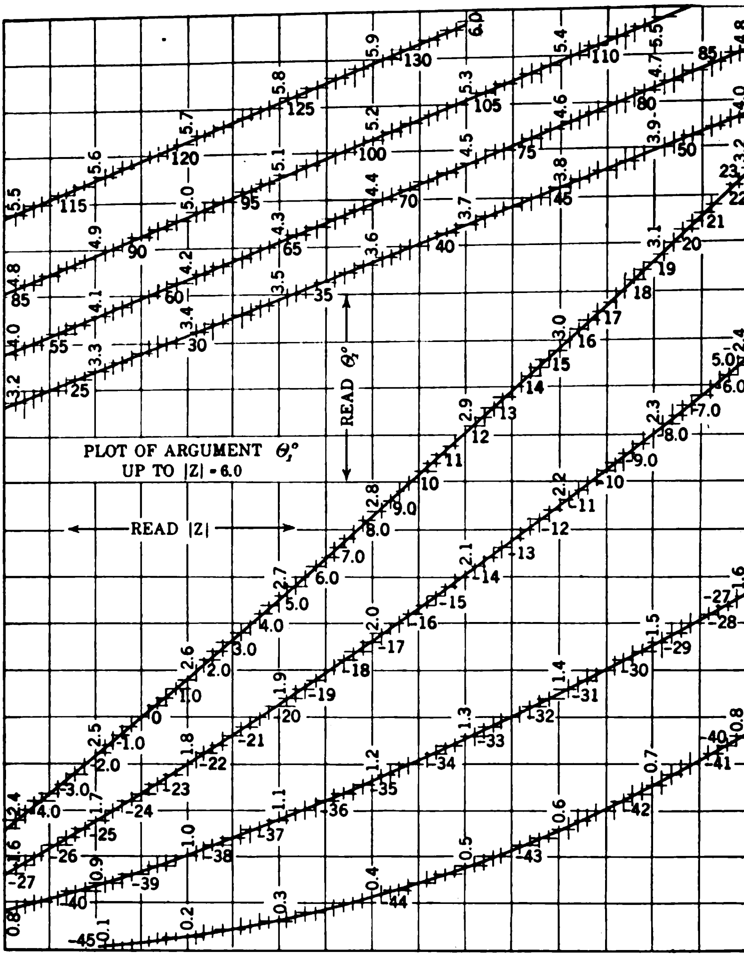


FIG. 24.—INTERPOLATION CHART FOR BESSEL FUNCTIONS OF THE FIRST ORDER OF THE SEMI-IMAGINARY QUANTITY $Z\,\overline{\backslash 45°}$

$$J_1(\alpha_0 x) = J_1(x\sqrt{4\pi\gamma\mu\omega}\,\overline{\backslash 45°}) = J_1(z\,\overline{\backslash 45°}) = \rho_1 \,\underline{/\theta_1°}$$

formulas (**42**), (**43**), (**54**), (**64**) and (**65**) as well as the skin effect ratios Z/R, R'/R, and L'/L.

Ber, Bei, Ber' and Bei' Functions. Certain functions, derived from Bessel's functions J_0 ($z\,\backslash 45°$), and J_1 ($z\,\overline{\backslash 45°}$), were intro-

duced by Lord Kelvin in his classical discussion of skin effect[12]. The ber function is the *r*eal component and bei the *i*maginary component of $J_0\ (z\ \diagdown 45°)$. Analogous relations connect the ber′ and bei′ functions with the corresponding real and imaginary components of $J_1\ (z\ \diagdown 45°)$. Thus, as is shown in Jahnke and Emde's " Funktionentafeln "[13] in the discussion of this subject,

$$J_0\ (z\ \diagdown 45°) = \text{ber}\ z + j\ \text{bei}\ z \qquad \text{numeric} \angle \quad (77)$$

and

$$J_1\ (z\ \diagdown 45°)\ \angle\tfrac{3\pi}{4} = \text{ber}'\ z + j\ \text{bei}'\ z \qquad \text{numeric} \angle \quad (78)$$

From which it is shown that

$$\frac{R'}{R} = \frac{\alpha_0 X}{2} \times \frac{\text{ber}\ (\alpha_0 X) \cdot \text{bei}'\ (\alpha_0 X) - \text{bei}\ (\alpha_0 X) \cdot \text{ber}'(\alpha_0 X)}{\text{ber}'^2\ (\alpha_0 X) + \text{bei}'^2\ (\alpha_0 X)} \qquad \text{numeric} \quad (79)$$

and

$$\frac{L'}{L} = \frac{4}{\alpha_0 X} \times \frac{\text{ber}\ (\alpha_0 X) \cdot \text{ber}'\ (\alpha_0 X) + \text{bei}\ (\alpha_0 X) \cdot \text{bei}'(\alpha_0 X)}{\text{ber}'^2\ (\alpha_0 X) + \text{bei}'^2\ (\alpha_0 X)} \qquad \text{numeric} \quad (80)$$

These formulas have the advantage that they give the solutions for R'/R and L'/L directly, after $\alpha_0 X$ is known, from reference to Tables of ber x, bei x, and ber $'x$ and bei $'x$. They have, however, the disadvantage of being longer, and of calling for more numerical work in computation than the corresponding formulas above presented (**68**), (**71**) and (**76**). Thus, in the case already considered, we find from ber-bei Tables, ber $3\ \diagdown 45° = -0.2214$, bei $3\ \diagdown 45° = 1.9376$; ber′ $3\ \diagdown 45° = -1.5698$, bei′ $3\ \diagdown 45° = 0.8805$.

Hence by (**79**)

$$\frac{R'}{R} = \frac{3}{2} \times \frac{-0.2214 \times 0.8805 - 1.9376 \times (-1.5698)}{(-1.5698)^2 + (0.8805)^2} = 1.318$$

and by (**80**),

$$\frac{L'}{L} = \frac{4}{3} \times \frac{-0.2214 \times (-1.5698) + 1.9376 \times 0.8805}{(-1.5698)^2 + (0.9805)^2} = 0.8456$$

12. Bibliography No. 9.
13. Bibliography No. 61.

TABLE IX—BESSEL FUNCTIONS OF THE ZERO AND FIRST ORDERS

of the semi-imaginary quantity ($z\ \backslash 45°$) expressed in polar form $\rho\ /\theta$ for expression $J_0\ (z\ \backslash 45°) = \rho_0\ /\theta_0$ and $J_1\ (z\ \backslash 45°) = \rho_1 / \theta_1$.

	$J_0\ (z\ \backslash 45°)$		$J_1\ (z\ \backslash 45°)$			$J_0\ (z\ \backslash 45°)$		$J_1\ (z\ \backslash 45°)$	
z	ρ_0	$/\theta_0$	ρ_0	$/\theta_1$	z	ρ_0	$/\theta_0$	ρ_1	$/\theta_1$
0.1	1.0000	0.15	0.0500	−44.931	5.1	6.6203	183.002	6.1793	97.533
0.2	1.0001	0.567	0.1000	−44.714	5.2	7.0339	187.071	6.5745	101.518
0.3	1.0002	1.283	0.1500	−44.350	5.3	7.4752	191.140	6.9960	105.504
0.4	1.0003	2.283	0.2000	−43.854	5.4	7.9455	195.209	7.4456	109.492
0.5	1.0010	3.617	0.2500	−43.213	5.5	8.4473	199.279	7.9253	113.482
0.6	1.0020	5.150	0.3001	−42.422	5.6	8.9821	203.348	8.4370	117.473
0.7	1.0037	7.000	0.3502	−41.489	5.7	9.5524	207.417	8.9830	121.465
0.8	1.0063	9.150	0.4010	−40.358	5.8	10.160	211.487	9.5657	125.459
0.9	1.0102	11.550	0.4508	−39.207	5.9	10.809	215.556	10.187	129.454
1.0	1.0155	14.217	0.5014	−37.837	6.0	11.501	219.625	10.850	133.452
1.1	1.0226	17.167	0.5508	−36.343	6.1	12.239	223.694	11.558	137.450
1.2	1.0319	20.333	0.6032	−34.706	6.2	13.027	227.762	12.313	141.452
1.3	1.0436	23.750	0.6549	−32.928	6.3	13.865	231.830	13.119	145.454
1.4	1.0584	27.367	0.7070	−31.011	6.4	14.761	235.897	13.978	149.458
1.5	1.0768	31.183	0.7599	−28.952	6.5	15.717	239.964	14.896	153.462
1.6	1.0983	35.167	0.8136	−26.768	6.6	16.737	244.031	15.876	157.469
1.7	1.1243	39.300	0.8683	−24.451	6.7	17.825	248.098	16.921	161.477
1.8	1.1545	43.550	0.9233	−22.000	6.8	18.986	252.164	18.038	165.486
1.9	1.1890	47.883	0.9819	−19.428	6.9	20.225	256.228	19.228	169.498
2.0	1.2286	52.283	1.0411	−16.732	7.0	21.548	260.294	20.500	173.510
2.1	1.2743	56.750	1.1022	−13.923	7.1	22.959	264.358	21.858	177.523
2.2	1.3250	61.233	1.1659	−11.000	7.2	24.465	268.422	23.308	181.536
2.3	1.3810	65.717	1.2325	− 7.970	7.3	26.074	272.486	24.856	185.554
2.4	1.4421	70.183	1.3019	− 4.838	7.4	27.790	276.540	26.509	189.571
2.5	1.5111	74.650	1.3740	− 1.613	7.5	29.622	280.612	28.274	193.589
2.6	1.5830	79.114	1.4505	1.701	7.6	31.578	284.674	30.158	197.608
2.7	1.6665	83.499	1.5300	5.099	7.7	33.667	288.736	32.172	201.627
2.8	1.7541	87.873	1.6148	8.570	7.8	35.896	292.798	34.321	205.646
2.9	1.8486	92.215	1.7045	12.111	7.9	38.276	296.859	36.617	209.670
3.0	1.9502	96.518	1.7998	15.714	8.0	40.817	300.920	39.070	213.692
3.1	2.0592	100.789	1.9012	19.372	8.1	43.532	304.981	41.691	217.716
3.2	2.1761	105.032	2.0088	23.081	8.2	46.429	309.042	44.487	221.739
3.3	2.3000	109.252	2.1236	26.833	8.3	49.524	313.102	47.476	225.764
3.4	2.4342	113.433	2.2459	30.622	8.4	52.829	317.162	50.670	229.790
3.5	2.5759	117.605	2.3766	34.445	8.5	56.359	321.222	54.081	233.815
3.6	2.7285	121.760	2.5155	38.295	8.6	60.129	325.282	57.725	237.842
3.7	2.8895	125.875	2.6640	42.171	8.7	64.155	329.341	61.618	241.868
3.8	3.0613	129.943	2.8226	46.067	8.8	68.455	333.400	65.779	245.896
3.9	3.2443	134.096	2.9920	49.978	8.9	73.049	337.459	70.222	249.925
4.0	3.4391	138.191	3.1729	53.905	9.0	77.957	341.516	74.971	253.953
4.1	3.6463	142.279	3.3662	57.840	9.1	83.199	345.577	80.048	257.981
4.2	3.8671	146.361	3.5722	61.789	9.2	88.796	349.566	85.466	262.011
4.3	4.1015	150.444	3.7924	65.743	9.3	94.781	353.693	91.259	266.041
4.4	4.3518	154.513	4.0274	69.706	9.4	101.128	357.751	97.449	270.071
4.5	4.6179	158.586	4.2783	73.672	9.5	108.003	361.811	104.063	274.102
4.6	4.9012	162.657	4.5460	77.638	9.6	115.291	365.868	111.131	278.133
4.7	5.2015	166.726	4.8317	81.615	9.7	123.110	369.958	118.683	282.164
4.8	5.5244	170.795	5.1390	85.590	9.8	131.429	373.983	126.752	286.197
4.9	5.8696	174.865	5.4619	89.571	9.9	140.300	378.002	135.374	290.229
5.0	6.2312	178.933	5.8118	93.549	10.0	149.831	382.099	144.586	294.266

Examples $J_0\ (3.1\ \backslash 45°) = 2.0592\ /100°.789$; $J_1\ (8.1\ \backslash 45°) = 41.691\ /217°.716$

Rosa and Grover[14] have worked out tables of R'/R and L'/L in accordance with formulas (**79**) and (**80**), for various values of $|\alpha_0 X|$, up to 100.

TABLE X—PROPAGATION CONSTANT OF THE MODULUS $|\alpha| = \sqrt{4\pi\gamma\mu\omega}$ FOR COPPER OF STANDARD CONDUCTIVITY, AT 20°C.
(ρ = 1724. absohm-cm., μ = 1.0) for various frequencies ~.

	$\|\alpha\|$	f	$\|\alpha\|$	f	$\|\alpha\|$	f	$\|\alpha\|$
5	0.4785	320	3.828	820	6.128	2600	10.91
10	0.6767	340	3.946	840	6.202	2700	11.12
15	0.8288	360	4.060	860	6.275	2800	11.32
20	0.9570	380	4.172	880	6.348	2900	11.52
25	1.070	400	4.280	900	6.420	3000	11.72
30	1.172	420	4.386	920	6.491	3100	11.92
35	1.266	440	4.488	940	6.560	3200	12.11
40	1.354	460	4.590	960	6.630	3300	12.29
45	1.436	480	4.688	980	6.699	3400	12.48
50	1.513	500	4.785	1000	6.767	3500	12.66
60	1.658	520	4.880	1100	7.097	3600	12.84
70	1.791	540	4.973	1200	7.413	3700	13.02
80	1.914	560	5.064	1300	7.716	3800	13.19
90	2.030	580	5.154	1400	8.007	3900	13.37
100	2.140	600	5.242	1500	8.288	4000	13.53
120	2.344	620	5.328	1600	8.560	4100	13.70
140	2.532	640	5.413	1700	8.823	4200	13.87
160	2.707	660	5.498	1800	9.079	4300	14.03
180	2.871	680	5.580	1900	9.327	4400	14.20
200	3.026	700	5.662	2000	9.570	4500	14.36
220	3.174	720	5.742	2100	9.806	4600	14.52
240	3.315	740	5.822	2200	10.04	4700	14.67
260	3.451	760	5.899	2300	10.26	4800	14.83
280	3.581	780	5.976	2400	10.48	4900	14.98
300	3.707	800	6.053	2500	10.70	5000	15.13

Example. At f = 2000 ~ α_0 = 9.570 $\backslash 45°$; α = 9.570 $\angle 45°$

Skin-Effect Impedance Ratio for Nonspiralled Stranded Conductors of Non-Magnetic Metal

In order to consider the impedance ratio for a stranded conductor in its simplest case, we may assume that all spirality effects are absent, and, therefore, that the conductor is stranded without any twisting, or, that if twisting occurs, the spirality effects of the twisting may be ignored. The effect of stranding a conductor will then be to increase its effective diameter, with-

14. Bibliography No. 85.

out altering the cross-section of metal. Let $A\ B\ C$, Fig. 25, be the cross-section of a solid round wire of great length, and remote from its return conductor, or from other disturbing conductors. Let its radius be X cm., and its substance have a conductivity γ abmhos per cm., and a permeability $\mu = 1$. Then let the above conductor be divided into a number of parallel strands, symmetrically insulated, spaced, and distributed; so that the total cross-section, including all insulation between strands, of the new stranded conductor $A\ B\ C$ is increased n times or

$$\pi X_1^2 = n\,\pi\,X^2 \qquad \text{sq. cm.} \quad (81)$$

and

$$X_1 = X\sqrt{n} \qquad \text{cm.} \quad (82)$$

The stranded conductor will not differ in permeability from the

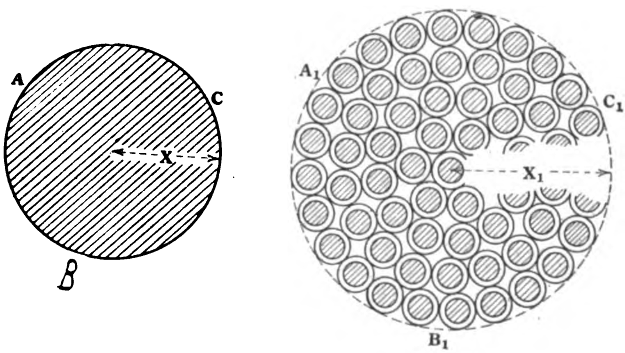


FIG. 25

solid conductor, but will differ therefrom in longitudinal electric conductivity. The stranded conductor will have the same total linear conductance as the solid conductor; but its average conductivity over the cross-section will be n times less. Consequently, the propagation constant α_1 of the stranded conductor will be:

$$\alpha_1 = \sqrt{4\,\pi\,\gamma_1\,\mu\,\omega}\ \underline{\backslash 45^\circ} = \sqrt{4\,\pi\,\frac{\gamma}{n}\,\mu\,\omega}\ \underline{\backslash 45^\circ} = \frac{\alpha_0}{\sqrt{n}}$$

$$\text{cm}^{-1}\ \angle \quad (83)$$

Therefore the quantity $\alpha_1 X_1$ for the stranded conductor is

$$\alpha_1 X_1 = \frac{\alpha_0}{\sqrt{n}} \cdot X\sqrt{n} = \alpha_0 X \qquad \text{numeric}\ \angle \quad (84)$$

or is the same as for the solid wire. We thus conclude, from an inspection of (**68**), that the impedance ratio Z/R, as well as its components R'/R, and $L'\omega/R$, are the same as for the metallically equisectional solid conductor. This is a property of conductors already known experimentally.[15]

Moreover, formulas (**42**) and (**43**), relating to the electric and magnetic forces and flux densities at any point within a solid conductor, clearly apply also to a non-spiralled symmetrically stranded conductor, if the radius x is expressed as a fractional part of the total radius X, in each case. Thus the values of η_x, i_x, $\mathcal{H}_x$ and $\mathcal{B}_x$, at half radial depth, bear the same complex numerical ratio to the corresponding values at the surface, in both stranded and solid conductors. The actual values of these

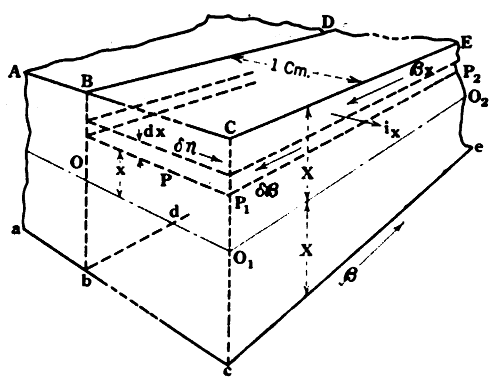


FIG. 26

quantities at the surface will not, however, be the same in both cases, although the computations are readily made with (**54**) and (**64**).

Skin Effect on Uniform Flat Strips of Indefinitely Great Width

The problem of skin effect in flat strips, of indefinitely great width, remote from disturbing alternating magnetic fields, seems to have first been solved by Lord Rayleigh[16] in 1886, and solutions have been given in various forms by a number of writers since that date. The steps in the demonstration are, however, presented here, because the forms of the final results are believed to

15. Pender, Bibliography No. 101.
16. Bibliography, No. 6.

offer particular advantages for engineers. Let $A\ B\ C\ c\ b\ a$, Fig. 26, be one edge of a long wide and flat strip, of uniform conductor, whose midplane is at $0 0_1 0_2$. The length of the strip is parallel to $0 0_1$, BC, or bc. The breadth across the strip is parallel to $0_1 0_2$, CE or ce. Between the cross sections at $B\ O\ b\ d\ B$ and $C\ O_1\ c\ e\ E$ there is supposed to be a length of 1 cm. of the strip. The half thickness of the strip OB, or O_1C, is taken as X cm. and any layer $P\ P_1\ P_2$ in the strip has a distance of x cm. from the midplane. Let γ be the conductivity of the metal, in abmhos per cm., μ the uniform permeability, ω the impressed angular velocity of the sinusoidal current in the steady state, in the direction $A\ B\ C$. Then, if the current density at the layer x is i_x absamperes per sq. cm. as indicated by the arrow, the magnetic intensity $\mathcal{H}_x$ will vanish at the midplane, will increase lefthandwards as we increase x positively, and also increase righthandwards as we descend to the lower surface at $x = -X$. Then, if we consider an elementary layer of thickness dx cm. at $P\ P_1\ P_2$, the magnetic flux density on the top of this layer will be greater than that at the bottom, the difference being, by electromagnetic theory:

$$d\mathcal{B}_x = 4\ \pi\ \mu\ i_x \cdot dx \qquad \text{gausses} \angle \quad (85)$$

or

$$\frac{d\mathcal{B}_x}{dx} = 4\ \pi\ \mu\ i_x \qquad \frac{\text{gausses}}{\text{cm. depth}} \angle \quad (86)$$

The increase of electric intensity $d\eta_x$ in the layer is

$$d\ \eta_x = \frac{d\mathcal{B}_x}{dt} \cdot dx = j\ \omega\ \mathcal{B}_x \cdot dx = \rho\ .\ di_x \qquad \frac{\text{abvolts}}{\text{linear cm.}} \angle \quad (87)$$

$$\therefore \frac{di_x}{dx} = j\ \frac{\omega\ \mathcal{B}_x}{\rho} = j\ \gamma\ \omega\ \mathcal{B}_x \qquad \frac{\text{absamperes}}{\text{cm.depth cm.}^2} \angle \quad (88)$$

Differentiating (**86**) with respect to x and substituting (**88**)

$$\frac{d^2\mathcal{B}_x}{d\ x^2} = j\ 4\ \pi\ \gamma\ \mu\ \omega\ \mathcal{B}_x = \alpha^2\ \mathcal{B}_x \qquad \frac{\text{gausses}}{\text{cm.}^2} \angle \quad (89)$$

where the propagation constant

$$\alpha = \sqrt{j\ 4\ \pi\ \gamma\ \mu\ \omega} = \sqrt{4\ \pi\ \gamma\ \mu\ \omega}\ \angle 45$$

$$= \sqrt{2\ \pi\ \gamma\ \mu\ \omega} + j\ \sqrt{2\ \pi\ \gamma\ \mu\ \omega} = \alpha_2 + j\ \alpha_2 \qquad \text{cm.}^{-1} \angle \quad (90)$$

Differentiating (**88**) with respect to x and substituting (**86**),

$$\frac{d^2\, i_x}{d\, x^2} = j\, 4\, \pi\, \gamma\, \mu\, \omega\, i_x = \alpha^2\, i_x \qquad \frac{\text{absamperes}}{\text{cm.}^4} \angle \quad (\mathbf{91})$$

The solutions of (**89**) and (**91**) are

$$i_x = A_1 \cosh \alpha x + B_1 \sinh \alpha x \qquad \frac{\text{absamperes}}{\text{sq. cm.}} \angle \quad (\mathbf{92})$$

$$\text{At } x = X,\ iX = A_1 \cosh \alpha X + B_1 \sinh \alpha X \qquad \text{" "} \angle \quad (\mathbf{93})$$

$$\text{at } x = -X,\ i_{-X} = A_1 \cosh(-\alpha X) + B_1 \sinh(-\alpha X) \qquad \text{" "} \angle \quad (\mathbf{94})$$

$$= A_1 \cosh \alpha X - B_1 \sinh(\alpha X) \qquad \text{" "} \angle \quad (\mathbf{95})$$

But i_x must have the same value in (**93**) and (**95**), which can only be satisfied with $B_1 = 0$. Consequently

$$i_x = A_1 \cosh \alpha x \qquad \frac{\text{absamperes}}{\text{sq. cm.}} \angle \quad (\mathbf{96})$$

where αx is a semi-imaginary quantity, or has $/45°$ as an argument. Dividing by (**93**), with $B_1 = 0$, we obtain

$$\frac{i_{xm}}{i_{Xm}} = \frac{i_{xr}}{i_{Xr}} = \frac{i_x}{i_X} = \frac{\cosh \alpha x}{\cosh \alpha X} \qquad \text{numeric} \angle \quad (\mathbf{97})$$

where the subscripts m indicate maximum cyclic, and the subscripts r root-mean-square values.

The average r.m.s. current density over the cross-section is

$$i_{qr} = \frac{1}{X}\int_0^X iX_r \cdot dx = \frac{1}{X} \cdot \frac{iX_r}{\cosh \alpha X} \cdot \int_0^X \cosh\, \alpha x \cdot dx$$

$$\frac{\text{absamperes}}{\text{sq. cm.}} \angle \quad (\mathbf{98})$$

$$= \frac{1}{\alpha X} \cdot \frac{iX_r}{\cosh \alpha X} \cdot \sinh \alpha X = iX_r \frac{\tanh \alpha X}{\alpha X}$$

$$\frac{\text{absamperes}}{\text{sq. cm.}} \angle \quad (\mathbf{99})$$

But $iX_r = \gamma\ \eta X_r$, is the uniform current density which the impressed e.m.f. would produce over the entire cross-section of the strip at zero frequency. Hence

$$\frac{iX_r}{i_{qr}} = \frac{iX_m}{i_{qm}} = \frac{Z}{R} = \frac{\alpha X}{\tanh\ \alpha X} \qquad \text{numeric} \angle \quad \textbf{(100)}$$

When αX has a modulus greater than 6.0, $\tanh\ \alpha X = 1.0\ \underline{/0^\circ}$ very nearly, and

$$\frac{Z}{R} = \alpha X \qquad \text{numeric} \angle \quad \textbf{(101)}$$

The skin-effect impedance ratio being $\alpha X/\tanh\alpha X$, let this complex quantity be

$$\frac{Z}{R} = M\ \underline{/\beta} \qquad \text{numeric} \angle \quad \textbf{(102)}$$

Then

$$\frac{R'}{R} = M \cos\ \beta \qquad \text{numeric} \quad \textbf{(103)}$$

and

$$\frac{L'\omega}{R} = M \sin\ \beta \qquad \text{numeric} \quad \textbf{(104)}$$

Dividing by ω,

$$\frac{L'}{R} = \frac{M}{\omega}\ \sin\ \beta \qquad \text{seconds} \quad \textbf{(104 a)}$$

As an example we may take the case of an indefinitely wide copper strip 0.2 cm. thick and operated at a frequency of 2183$\sim$;

so that

$$\alpha = \sqrt{4\ \pi \cdot 1 \cdot \frac{1}{1724} \cdot 2\ \pi \cdot 2183\ \underline{/45^\circ}} = 10\ \underline{/45^\circ}.$$

Then $X = 0.1$ cm. and $\alpha X = 1.0\ \underline{/45^\circ}$.

By Tables,[17] $\tanh\ 1.0\ \underline{/45^\circ} = 0.9308\ \underline{/27^\circ.044}$

17. Kennelly, Bibliography No. 99.

so that $$\frac{Z}{R} = \frac{1\cdot 0\ \underline{/45^\circ}}{0.9308\ \underline{/27^\circ.044}} = 1.074\ \underline{/\ 17^\circ}.956$$

$$= 1.022 + j\,0.331; \text{ and } \frac{R'}{R} = 1.022$$

The skin effect resistance ratio is therefore 1.022.

Again, using (**97**) and (**100**)

$$\frac{i_{xm}}{i_{qm}} = \frac{i_{xr}}{i_{qr}} = \frac{\alpha X}{\sinh \alpha X} \cdot \cosh \alpha x = \frac{\cosh \alpha x}{\left(\frac{\sinh \alpha X}{\alpha X}\right)} \qquad \text{numeric } \angle \ (\mathbf{105})$$

The complex $\frac{\sinh \alpha X}{\alpha X}$ has been tabulated and charted for the argument $\underline{/45^\circ}$ up to $|\alpha X| = 3.0$. Thus in the case considered, by Tables, $\frac{\sinh 1.0\ /45^\circ}{1.0\ /45^\circ} = 1.0055\ /9^\circ.531$; so that in this case

$$\frac{i_{xr}}{I_{qr}} = 0.9945\ \overline{\backslash 9^\circ.531} \cosh \alpha x \qquad \text{numeric } \angle \ (\mathbf{106})$$

At the midplane, where $x = 0$, and $\cosh 0\ /45^\circ = 1.0\ \underline{/0^\circ}$, the local current density is about 0.5 per cent. less than the average current density and lags behind it 9°.5. At the surface, where $X = 0.1$, and $\alpha X = 1.0\ /45^\circ$, $\cosh 1.0\ /45^\circ = 1.080\ \underline{/27^\circ.487}$; so that $\frac{iX_r}{i_{qr}} = 1.074\ \underline{/\ 17^\circ.957}$ and the surface current density is 7.4 per cent greater than the average and leads it nearly 18°.

The external skin thickness δ cm., which, carrying the surface current density iX_r, would be the equivalent of the half thickness of strip carrying the average current density i_{qr}, is defined by the condition

$$\frac{\delta}{X} = \frac{R}{R'} \qquad \text{numeric } (\mathbf{107})$$

or

$$\delta = X\,\frac{R}{R'} \qquad \text{cm. } (\mathbf{108})$$

or

$$\delta = \left|\frac{\tanh \alpha X}{\alpha X}\right| \frac{X}{\cos \beta} \qquad \text{cm. } (\mathbf{109})$$

For frequencies sufficiently high to make $|\alpha X| > 6.0$, this approximates closely to

$$\delta = \left|\frac{1}{\alpha}\right| \sqrt{2} = \frac{1}{\alpha_2} \qquad \text{cm.} \quad \textbf{(110)}$$

Thus, in the case considered, $\dfrac{\tanh 1.0 \ \underline{/45^\circ}}{1.0 \ \underline{/45^\circ}}$ is, by Tables, $\dot{0}.9308$ $\backslash 17^\circ.\overline{956}$, and $\delta = 0.09308/\cos(17^\circ.956) = 0.009308/0.9513$, $= 0.0978$ cm., approaching more and more nearly to $1/\alpha_2$ cm. as the frequency increases.

Returning to (**89**), the solution for $\mathfrak{B}_x$ is

$$\mathfrak{B}_x = A_2 \cosh \alpha x + B_2 \sinh \alpha x \qquad \text{gausses} \angle \quad \textbf{(111)}$$

where α, as before, stands for the semi-imaginary

$$\sqrt{4 \pi \gamma \mu \omega} \ \underline{/45^\circ} = \alpha_2 + j \alpha_2 \qquad \text{cm.}^{-1} \angle$$

In order that $\mathfrak{B}_x = -\mathfrak{B}_{-x}$; *i.e.* that the flux-densities at opposite surfaces shall be equal and opposite it is necessary that A_2 should vanish, and this leaves

$$\mathfrak{B}_x = \mathfrak{B}_2 \sinh \alpha x \qquad \text{gausses} \angle \quad \textbf{(112)}$$

and

$$\frac{\mathfrak{H}_{xm}}{\mathfrak{H}_{Xm}} = \frac{\mathfrak{H}_{xr}}{\mathfrak{H}_{Xr}} = \frac{\mathfrak{B}_{xr}}{\mathfrak{B}_{Xr}} = \frac{\sinh \alpha x}{\sinh \alpha X} \qquad \text{numeric} \angle \quad \textbf{(113)}$$

The r.m.s. surface flux density $\mathfrak{B}X_r$ is determined by the fact that if I_r is the r.m.s. value of the current per unit breadth of strip, in absamperes per cm.

$$\mathfrak{B}_{Xr} = 2 \pi \mu I_r \qquad \text{gausses} \angle \quad \textbf{(114)}$$

and

$$\frac{\mathfrak{B}_{xr}}{\mathfrak{B}_{Xr}} = \frac{2 \pi \mu I_r}{\sinh \alpha X} \cdot \sinh \alpha x \qquad \text{gausses} \angle \quad \textbf{(115)}$$

Thus in the case considered, if the r.m.s. current carried is say 1 ampere per cm. of breadth, $I_r = 0.1 \ \underline{/0^\circ}$, $\sinh 1.0 \ \underline{/45^\circ} = 1.0055 \ \underline{/54^\circ.531}$. Hence

$$\mathfrak{B}_{xr} = \frac{0.6283 \ \underline{/0^\circ}}{1.0055 \ \underline{/54^\circ.531}} \cdot \sinh \alpha x \qquad \text{gausses} \angle \quad \textbf{(116)}$$

At the midplane where $x = 0$, $\sinh \alpha x = 0\underline{/45°}$, and $\mathcal{B}_{0r} = 0\backslash\overline{9°.531}$, *i. e.* vanishing flux density, lagging 9.°53 behind the phase of average current.

It will thus be observed that the change in form of a linear conductor from a solid cylinder to a wide flat strip, has the effect of substituting hyperbolic functions of a semi-imaginary variable αx for Bessel functions of a closely related semi-imaginary variable $\alpha_0 x$ where $|\alpha| = |\alpha_0|$, and $\alpha = j\,\alpha_0$, the form of the fundamental equations (**42**)—(**97**) and (**43**)—(**113**) remaining unchanged.

As was first pointed out by Steinmetz[18], the conditions of current density as we penetrate into the strip, correspond to those of current strength in a long pair of parallel a-c. lines, with distributed constants, a millimeter of depth corresponding perhaps to hundreds of kilometers of line length. In fact, formula (**97**) is identical with that which expresses the current strength at any point of a pair of wires in a telephone cable, with negligible inductance and leakance, short circuited at the distant end, which then corresponds to the midplane in the strip. Similarly, formula (**113**) for the ratio of magnetic voltage gradients in the strip, is identical with the formula for electric voltages across such a pair of wires. The propagation constant α is a semi-imaginary in each case, the linear leakance corresponding to conductivity, and linear resistance to permeability. Just as in the cable, the wave length is[19]

$$\lambda = \frac{2\,\pi}{\alpha_2} = \frac{2\,\sqrt{2}\,\pi}{|\alpha|} \qquad \text{length units} \quad (\mathbf{117})$$

so in the strip, the wave length is given by this formula, cm. or the c.g.s. length unit being employed. Thus, in the case considered, where $\alpha = 10\,\underline{/45°}$, and α_2, the imaginary component

of α is 7.071, $|\alpha| = 10$, and $\lambda = \dfrac{6.283 \times 1.414}{10} = 0.8885$ cm.

That is, the rate of change of phase in the propagation of electric and magnetic intensities as we penetrate the strip, is one complete cycle, or 360 degrees, for 0.8885 cm. *i.e.* 405° per cm., and 40°.5 per mm. Reflections from the midplane in a shallow strip, disturb

18. Bibliography No. 66.

19. Bibliography No. 84.

this relation, which tends to be presented more nearly accurately as the thickness of the strip is increased.

The skin-effect theory of indefinitely wide strips, as outlined above, appears to be of but little service in the actual use of ordinary copper-strip conductors, owing to the large disturbing magnetic effects at the edges. It is, however, useful in relation to the use of copper-tube conductors, and especially when these have large diameter and thin wall. The wall thickness X cm. should then correspond to the half-thickness X of a wide strip[20]; since the flux density must vanish at the inside wall of such a tube.

There is, however, another reason why the above skin-effect theory of strips should be considered, in spite of its very imperfect application to narrow strips; namely, because it applies with but little modification to the important case of magnetic skin effect in steel strips or laminae of sheet steel, if the permeability can be taken as constant at an average value. The discussion of that theory is out of place here; but it may be permissible to point out that formula (**97**) applies to the magnetic lamina case, when flux densities $\mathfrak{B}_x$ and $\mathfrak{B}_X$ substituted for current densities i_x and i_X, and formula (**93**) likewise applies to the magnetic case, when electric current densities i_x and i_X are substituted for $\mathfrak{B}_x$ and $\mathfrak{B}_X$. That is, the theory of the magnetic strip case follows the same course as that of the electric strip case, above outlined, when magnetic and electric flux densities are mutually interchanged. Formulas (**99**), (**100**), (**109**), (**110**), (**113**) and others, then apply to both cases. It is evident that complex hyperbolic functions are a natural key to the actions in both cases.

Empirical Formula for Narrow Strips 1.6 mm. Thick

The curves of Fig. 10, present the resistance ratios of three widths of 1.6 mm. copper strip up to 5000 $\sim$ at 60 cm. spacing. From these curves an approximate empirical relation has been found between about 1000 and 5000 $\sim$, namely

$$\frac{R'}{R} = 0.308\, f^{0.21}\, w^{0.163} \qquad \text{numeric} \quad (\mathbf{118})$$

where f is the impressed frequency, and ω the strip width in cm. This empirical formula is clearly inapplicable at low frequencies; but serves to indicate the effect of increasing strip width for the range covered in these tests.

20. Bibliography No. 101, p. 1284.

List of Symbols Employed

A external inductance of a test loop (abhenrys).

A, B, arbitrary constants of electric current density in integration equation (absamperes per sq. cm. $\angle$).

A', B', arbitrary constants, magnetic intensity in integration equation (gilberts per cm. $\angle$).

A_1, B_1, arbitrary constants electric current density in integration equation (absamperes per sq. cm. $\angle$).

A_2, B_2, arbitary constants magnetic flux density in integration equation (gausses $\angle$).

a, length of a rectangular loop (cm.).

$\alpha = \sqrt{4\pi\gamma\mu\omega}\ \underline{/45^\circ}$ propagation constant for a flat strip, a positive semi-imaginary (cm.$^{-1}$ $\angle$).

$\alpha_0 = \sqrt{4\pi\gamma\mu\omega}\ \backslash 45^\circ$ propagation constant for a solid cylinder, a negative semi-imaginary (cm.$^{-1}$ $\angle$).

α_1, propagation constant for a stranded cylinder, a negative semi-imaginary (cm.$^{-1}$ $\angle$).

α_2, imaginary or real component of a semi-imaginary propagation constant (cm.$^{-1}$).

β, argument of a complex number expressing a skin-effect impedance ratio (radians or degrees).

$\mathfrak{B}_x$, $\mathfrak{B}_{xm}$, $\mathfrak{B}_{xr}$, instantaneous, maximum cyclic, and r.m.s. values of flux density at point of radius x (gausses $\angle$).

b, interaxial distance between two parallel wires (cm.)

$\gamma = 1/\rho$, electric conductivity of material (abmhos per cm.)

C, skin-effect inductance ratio L'/L (numeric)

d, diameter of round conductor (cm.)
also sign of differentiation.

δ, thickness of skin carrying the same current at surface flux density as the whole cross-section at varying densities (cm).
also the argument of a complex quantity z/δ in a Bessel function (radian or degree).

$\epsilon = 2.71828\ldots$ Napierian base.

η_x, η_{xm} η_{xr}, instantaneous, maximum cyclic and r.m.s. values of electric intensity at point of radius x (abvolts per cm. $\angle$)

η_X, η_{Xm}, η_{Xr}, instantaneous, maximum cyclic and r.m.s. values of electric intensity at surface of radius X (abvolts per cm. $\angle$).

f, frequency of impressed alternating current (cycles per sec.)

$\mathcal{H}_x$, $\mathcal{H}_{xm}$, $\mathcal{H}_{xr}$, instantaneous, maximum cyclic and r.m.s. values of magnetic intensity at point of radius x (gilberts per cm. $\angle$).

I_M, I_X, r.m.s. alternating currents in the sides of a Heaviside bridge (amperes $\angle$).

I_m, I_r, maximum cyclic and r.m.s. values of alternating current in a conductor (absamperes $\angle$).

i_X, i_{Xm}, i_{Xr}, instantaneous maximum cyclic, and r.m.s. values of current density at surface of radius X (absamperes per sq. cm. $\angle$).

i_x, i_{xm}, i_{xr}, instantaneous maximum cyclic, and r.m.s. values of current density at radius x (absamperes per sq. cm. $\angle$).

i_q, i_{qm}, i_{qr}, instantaneous, maximum cyclic, and r.m.s. values of vector average current density over cross-section (absamperes per sq. cm. $\angle$).

$j = \sqrt{-1}$

$J_0(z)$ zero-order Bessel function of first kind, for a variable z (numeric).

$K_0(z)$, zero-order Bessel function of second kind, for a variable z (numeric).

$J_1(z)$ first-order Bessel function of first kind, for a variable z (numeric).

$K_1(z)$, first-order Bessel function of second kind, for a variable z (numeric).

K, twice the mutual inductance per turn of the secondary winding in Heaviside bridge (henrys per turn).

k, twice the resistance of one cm. length of Heaviside-bridge slide wire (ohms per cm.).

L, linear internal inductance of conductor in test loop without skin effect (abhenrys per linear cm.).

L, inductance of the test loop at zero frequency (henrys or abhenrys).

L', inductance of the test loop at test fequency, with skin-effect (henrys or abhenrys).

also linear internal inductance of conductor at test frequency, with skin-effect (abhenrys per linear cm.).

L''_P, L''_X, inductance in the P and X arms of a Heaviside bridge (henrys).

L'_P, L'_X, inductances in the P and X arms of a Heaviside bridge excluding slide wire (henrys).

l_0, reading on Heaviside-bridge slide wire with loop short-circuited (cm.).

l_1, reading on Heaviside-bridge slide wire with loop inserted (cm.).

l, total length of slide wire in Heaviside bridge (cm.).

λ, wave-length of propagation (cm.).

$M = |Z/R|$, modulus of a complex number expressing a skin-effect impedance ratio (numeric).

μ, permeability of a substance to magnetic force [gausses per (gilberts per cm.)].

also twice the inductance change per cm. of Heaviside bridge slider abhenrys /cm.

m, a constant coefficient of the variable in a Bessel function (numeric $\angle$).

m, mutual inductance in a Heaviside bridge wire (henrys).

m_0, mutual inductance in a Heaviside bridge wire for balance with loop shorted (henrys).

m_1, mutual inductance in a Heaviside bridge wire for balance with loop inserted (henrys).

n, the general term number in an expanded series, also ratio of amplification of cross-section in stranding a conductor (numeric).

n_0, number of turns in secondary of mutual inductance in Heaviside bridge wire for balance with loop shorted (numeric).

n_1, number of turns in secondary of mutual inductance in Heaviside bridge wire for balance with loop inserted (numeric)

p, order of a Bessel function.

$\pi = 3.14159\ldots.$

R, resistance to continuous currents of the test loop without skin effect (ohms).

also linear resistance to continuous currents of the test loop (absohms per linear cm.).

R' resistance to alternating currents of the test loop with skin-effect (ohms).

also linear resistance to alternating currents of the test loop with skin effect (absohms per linear cm.).

R_P'', R_X'', resistances in P and X arms of a Heaviside bridge (ohms).

R_P', R_X', resistances in P and X arms of a Heaviside bridge excluding slide wire (ohms).

r.m.s., contraction for root-of-mean-square.

$\rho = 1/\gamma$, resistivity of material (absohms cm.).

t, time elapsed from a selected epoch (seconds).
w, width of a flat strip (cm.).
X, external radius of a cylindrical conductor (cm.).
x, radial distance of a point on a cylindrical cross-section from the axis (cm.).
X, half thickness of a flat strip conductor (cm.).
X, total radial thickness of the wall of a tubular conductor (cm).
X', linear reactance of conductor in test loop, with skin-effect (absohms per linear cm.).
X, equivalent external radius of a stranded cylindrical conductor (cm.).
$Z = R' + j X'$, linear impedance of conductor in test loop with skin-effect (absohms per linear cm. $\angle$).
Z_M, Z_N, Z_P, Z_X, impedances in the four arms of a Heaviside bridge (ohms $\angle$).
$\omega = 2\pi f$, angular velocity of impressed alternating current (radians per second).
$\sim$, sign for "cycles per second."
$|z|$, sign for the modulus of a complex quantity z (numeric)
$\underline{z}$ sign for the argument of a complex quantity z (radians or degrees).

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DEISEL ENGINES FOR GENERATOR DRIVE

BY CHARLES LEGRAND

ABSTRACT OF PAPER

The author describes some investigations made in Europe of Diesel engines of large capacity, with a view to their suitability for driving generators of 500 to 1000 kw. capacity under conditions prevailing in mining camps in the Southwest.

LATE in the year 1912, the writer investigated the suitability of Diesel engines for driving generators of 500 kw. to 1000 kw. capacity under conditions generally prevailing in mining camps in the South west. At that time no American made engines of sufficient size were available and the investigation was carried on in Europe, mostly in Belgium.

Four-cycle engines of 175 effective b.h.p. per cylinder, had been in use for several years and the results of their operation known. Cylinders of 250 effective b.h.p. were made but I did not see any.

Two-cycle engines of 250 effective b.h.p. per cylinder, had been in operation for a short time, but no data as to maintenance or repairs was available. Engines with cylinders of 600 effective b.h.p. were under construction after shop experiments had been carried on with one single cylinder of that size. One cylinder of 1000 effective b. h.p. was being experimented upon, and builders were ready to take orders for engines using this size cylinder. All of the above cylinder ratings were for sea level conditions. The four cycle engines inspected had trunk pistons air cooled. The two cycle engines had water cooled pistons with cross-head and slides.

All engines used forced lubrication for cylinders. Both types were used successfully to drive alternators in parallel, the generators being equipped with damping windings. For a given number of cylinders, the four-cycle engine required a heavier flywheel. Heavy oils could be used in both types with proper arrangement for heating the oil and using a light oil at start and finish of a run.

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The fuel consumption per b.h.p. of a four-cycle engine is from 7 per cent to 10 per cent less than that of the two-cycle engine, depending on the load and, for both types, is practically independent of the size of the engine.

The four-cycle engine is simpler, having no scavenging pump or moving water connections to the piston.

The two-cycle engine has no exhaust valve, the exhaust taking place through ports in the cylinder wall; this is an advantage when using oil containing sulphur, as the exhaust valve is principally affected when sulphuric acid is formed in the cylinder and condenses on the seat of the exhaust valve, requiring frequent grinding of this valve.

The scavenging pump is an advantage on engines to be used at high elevations, as by increasing the size of this pump, the pressure in the cylinders at the beginning of the stroke can be increased above atmospheric pressure and restore sea level conditions, if found advisable, at a comparatively small increase of fuel consumption. This could be done on four-cycle engines by the addition of an air pump, but would complicate this type of engine.

The lubricating oil consumption of four-cycle engines is higher per horse power than that of the two-cycle engine. The total consumption of lubricating oil of a 525-h.p. three-cylinder, four-cycle engine in actual practise being approximately five gallons per b.h.p.—year of engine rating, while that of a five-cylinder two-cycle engine of 1250 b.h.p. is 2.5 gallons per b.h.p-year, both being on sea level rating of engines and for continuous service.

The proportion of cylinder oil to engine oil used in the two-cycle type seems to be greater than in the four-cycle. In the four-cycle, the cylinder and engine oils used are about the same, according to builder's statements, while in the two-cycle, the cylinder oil is approximately twice the engine oil from actual practise during three months.

The four-cycle engine takes a little more room and is heavier than the two-cycle engine of the same power.

Briefly stated, the advantages of the four cycle engine were; well established type with known maintenance and repair costs, smaller fuel consumption, greater simplicity; those of the two cycle engine were; less lubricating cost, steadier running, less liability of trouble from sulphur in fuel oil, greater output per cylinder, less cost per horse power especially at high altitudes.

After due consideration, the company with which I am connected decided to try the two-cycle engine in actual practise, and two five-cylinder engines rated at 1250 b.h.p. at seal level, direct connected to 815-kv-a. 6600-volts, three-phase, 180-revolution generators, were installed. One of them has been in operation since December 1914, and the other since March 1915; the load at present is so small that only one engine is operated at less than 25 per cent capacity, and it is too early to give any results of operation; however, from the numerous tests which we have made parallel operation is quite easy.

The exciters are direct connected to engines and run in parallel on the regulator.

Before paralleling the generators, the exciters were run in parallel for half an hour, one engine having a slightly variable load of 90 kw. and the other no load. The variation of load on the two exciters did not exceed 10 amperes from the average of 90 amperes.

The two generators were then paralleled on a total load of 90 kw. and the variation of load between engines could hardly be seen on indicating wattmeters. After a sufficient length of time to satisfy ourselves that there was no difficulty in parallel running, we cut off the fuel supply on one cylinder of one engine, then on two cylinders. With one engine running on three cylinders and the other on five cylinders the load varied approximately 30 kw. between the two engines, after the governor had been adjusted to divide the load about equally. This test was then repeated after increasing the total load to 200 kw., with the same results. Later on, the two engines were connected in parallel, then the fuel supply was cut off altogether on one engine, running its generator as a motor; the fuel supply was then put on again, but we have been unable to make the generators fall out of step and they behave much better than any compound steam engines with which the writer has had experience. The current readings were too small to get reliable data on interchange of current between generators.

The engines use California crude oil of about 16 deg. B gravity, heated to 120 deg. fahr. by means of the circulating water of the engines, except at start and finish of a run, when a lighter oil is used so that it will flow when cold.

The writer hopes to be able to publish some operating data after the engines have been operated for a few months more.

Regarding cost of installation as compared to a steam plant,

this has to be figured for each particular case. The character of the load has an important bearing on the total capacity of generating machinery to be installed.

With a steady load the total capacity of units is practically the same, as both have the maximum efficiency at rated load.

With a variable load subject to high peaks, the Diesel engine plant would require a greater capacity than the steam plant, as like all internal combustion engines, the Diesel engine has little overload capacity.

With conditions prevailing generally in Arizona, on rated capacity of plant installed for total power between 1000 and 2500 kw. the cost of a Diesel engine plant compares favorably with a high grade steam plant using condensing Corliss engines, superheater and economizer in boiler plant.

In designing a Diesel engine plant it is well to remember that the fuel consumption per effective b.h.p. is practically independent of the size unit used, that an engine can be started and put under full load in a very short time so that a greater number of units can be used if it suits the load conditions better.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 17, 1915.

A LARGE ELECTRIC HOIST

BY WILFRED SYKES

ABSTRACT OF PAPER

The paper describes an electric hoist recently installed in a mine at Butte, Mont., having a depth of shaft of 4000 ft., net weight of load 14,000 lb., weight of skip and cage, 9000 lb. and maximum hoisting speed 3000 ft. per min. Some results of operations are given. This hoist is of special interest as being the largest electric hoist in the world and containing some important departures from previous practise.

THE MINING conditions in Butte require the handling of large quantities of ore from depths of 2000 to 4000 ft. and eventually from 5000 ft. In the past steam hoists were used, but the difficulty of getting good water supply, and the high cost of fuel, made their operation expensive. Cheap hydroelectric power is available, and a few years ago an attempt was made to decrease the cost of operation and still utilize the greater portion of the existing hoists, by arranging them for compressed air operation. A central compressor plant was installed, the compressors being driven by synchronous motors for supplying the air not only to the hoists but for other underground operations. Although the central compressor station is the largest in existence, the supply of air is not altogether adequate and with the continually increasing requirements for underground working, the alternative had to be faced of either increasing the compressor station, if new hoists are added, or of driving new hoists by some other means. The use of compressed air is attended by all the usual difficulties of transmission, leakages, etc and in order to obtain its economical operation preheaters are necessary for each hoist which require the use of fuel and labor to fire them. The air hoist has the same characteristics as the steam hoist, and is therefore not very satisfactory from the standpoint of maneuvering. It has of course a large number of wearing parts, requiring attention and the maintenance is at least as high as the steam hoist.

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Recently the North Butte Mining Co. put into operation a new shaft and after a consideration of the various factors it was decided to use an electrically driven hoist instead of compressed air. The new shaft will be finally sunk to a depth of 5000 feet and the requirements of the hoist are representative of the conditions in the Butte field. The operating conditions are as follows:

Depth of shaft—4000 ft., eventually 5000 ft.; Net weight of load, 14,000 lb.; Weight of skip and cage, 9000 lb.; Size of rope, $1\frac{5}{8}$-in.—4.1 lb. per foot., Drums, 12 ft. in diameter. Maximum hoisting speed 3000 ft. per minute. Normal hoisting speed 2700 ft. per minute.

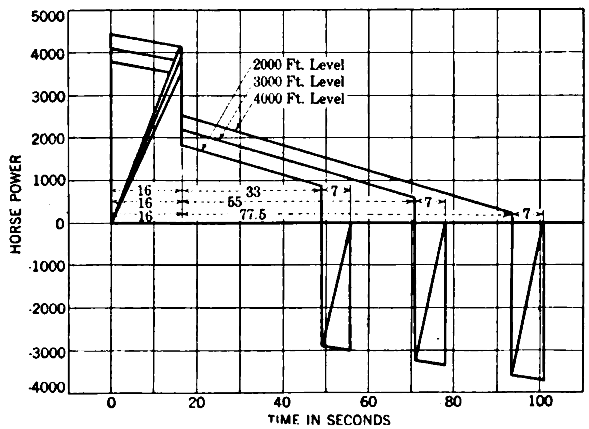


FIG. 1—NORTH BUTTE MINING COMPANY HIOST CYCLE

To meet the above conditions it was estimated that the load on the motor for the various depths would be in accordance with the diagram, Fig. 1. These estimates show that the power peaks will be approximately 4500 h.p., and, under the conditions that power is purchased in Butte, the cost would be excessive if a hoist operated by an induction motor were installed. Apart from other conditions of operation, this feature alone was sufficient to eliminate an alternating-current motor drive for the hoist. It was therefore decided to use a flywheel motor-generator set which would limit the input to the equipment, the peaks being carried by the flywheel. It was not attempted to install a flywheel of sufficient capacity to completely equalize the load as this would have required a much

larger wheel than the one installed and the continuous losses would have been very greatly increased. It was estimated that by the use of a 50-ton flywheel the input to the hoist could be limited to the following figures during normal operation:

Depth—2000 ft. 3000 ft. 4000 ft.

Input—1250 h.p. 1420 h.p. 1850 h.p.

The efficiency of electric hoisting with this system is naturally lower than if the power were utilized more directly, due to the conversion and friction losses. The elimination of the elaborate controlling apparatus, that would be necessary, the absolute control over the speed of hoisting, the generally more satisfactory results, and the elimination of high peaks are sufficient compensation for the extra power required. The calculated

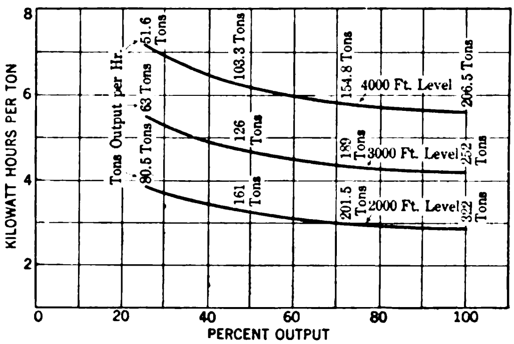


FIG. 2—NORTH BUTTE MINING COMPANY—POWER CONSUMPTION CURVES OF HOIST

efficiency of operation is shown in Fig. 2, which shows the power input per ton hoisted from various loads. Considerable importance is attached to the reduction of the light-load losses to a minimum, as the flywheel motor-generator set runs continuously, only shutting down about once a month for cleaning, etc. Consequently the lower the light-load losses the higher would be the general overall efficiency of the equipment. The mining conditions in Butte call for hoisting at full capacity for four or five hours at a time twice each day. The remainder of the period of hoist is handling waste, timber and men. Guarantees under very heavy penalties were therefore required for the light-load losses and as they could be readily measured there was no difficulty in checking the manufacturer's figures. Estimates of power consumption per ton

of material hoisted cannot be readily checked without special efforts being made to operate the hoist exactly on the cycle on which the estimates are based, and as it is almost impossible to determine accurately the mechanical efficiency of the hoist, such tests could not be relied upon to check the efficiency of the apparatus. From the individual efficiency curves of the machines and the known light load losses, the power required under any stated condition can be readily calculated.

The hoist consists of two drums, each fitted with a clutch, post brake and band brake. The drums are mounted on a shaft supported by three bearings, the shaft having a flanged coupling to connect to the motor shaft. The clutches and post brakes are operated by oil cylinders, the pressure being supplied by an accumulator with an electrically operated triplex pump. The band brakes are operated by hand wheels. All of the operating levers are grouped on a large elevated platform with double stairways. The control and reverse levers are separate, but so interlocked that when the control lever is in the " on " position the reverse lever cannot be moved.

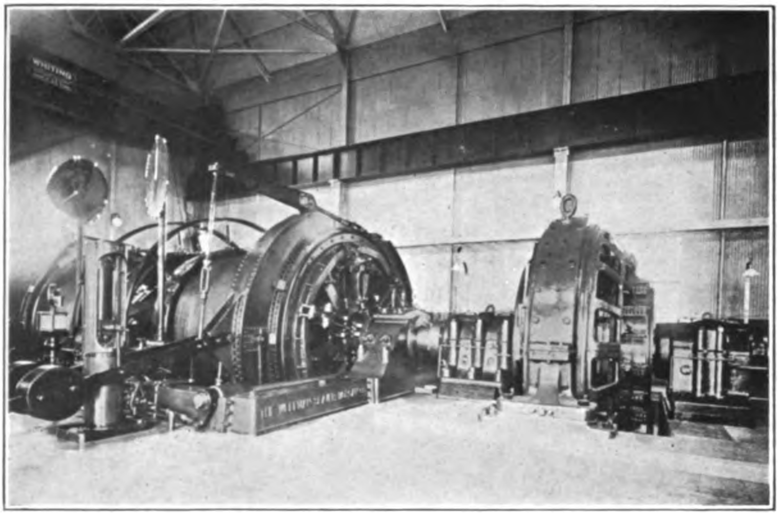
The safety devices include a mechanism for moving the control lever to the " off " position when the skip has reached a predetermined point, holding this lever in this position until the reverse lever has been moved to its opposite position, the operator being thereby prevented from starting the hoist in the wrong direction.

There are two solenoids which automatically apply the post brakes if the skip is carried too far after the current has been cut off.

An indicator with a large dial is provided for each drum, and for accurately spotting the skip or cage, the brake rings on the drums next to the middle bearing are extended 8 in., affording a large surface on which to paint marks.

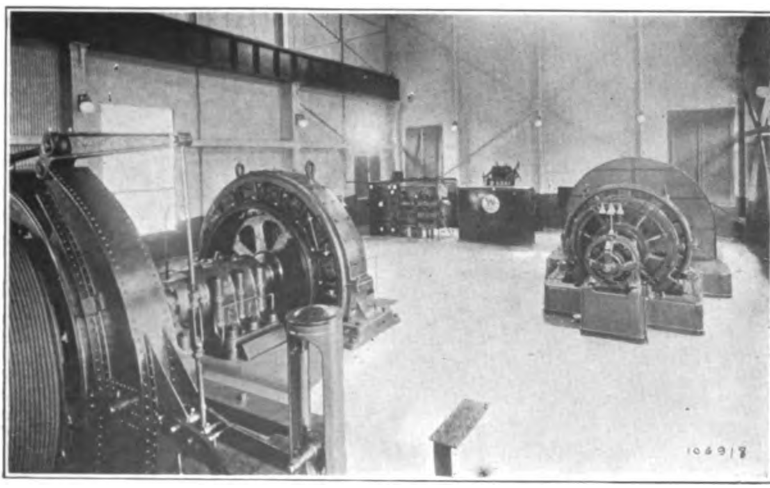
On the platform there are mounted in front of the operator a panel holding a voltmeter and an ammeter, also a target which is connected to the reverse lever showing which drum is hoisting. Grouped around the sides of the platform are the signal gongs, lights and telephone.

The drums are 12 ft. in diameter by 9 ft. 4 in. face, each with turned grooves to hold 5000 feet of $1\frac{5}{8}$-in. rope in two layers. The drum shell, brake rings and spiders are made of cast steel, the latter being fitted with heavy bronze bushings, each bushing being provided with four large grease cups for lubrication.



[SYKES]

FIG. 3—HOIST AND MOTOR



[SYKES]

FIG. 9—FLYWHEEL MOTOR-GENERATOR SET AND CONTROL APPARATUS

The clutches are of the flat friction type consisting of two heavily ribbed annular rims faced with wood, supported on a six-arm spider keyed to the shaft. These rings clamp a flat steel plate bolted to the drums and are moved by six sets of toggle arms connected to a sliding sleeve and rock shaft and operated by an oil cylinder. All of the parts of the clutches are made of steel. The clutches are designed to take a load of 50,000 pounds on a 12-ft. diameter, and all of the parts are figured for a factor of safety of not less than eight. The clutches and the motor were subjected to a load of two and a half times their rated capacity and under this load developed no weakness.

The post brakes are made of plates and angles in the form of a box girder and are lined with basswood blocks readily renewed. The post brakes are the parallel acting type applied by gravity and released by oil cylinders.

The band brakes are for emergency service and are operated by means of hand wheels and screws. Proper provision has been made for operating these by power later on if desired.

The bearings for the drum shaft are of the pedestal type with quarter boxes adjusted both vertically and horizontally. They are lubricated by a continuous gravity feed oiling system with the necessary tank, filters and pump, the latter being driven directly from the drum shaft, oil being supplied to the bearings whenever the hoist is in operation.

The drum shaft is of open hearth forged steel, 22 in. in diameter by 40 ft. $5\frac{1}{2}$ in. long, and has a flanged coupling forged at one end to be connected to the motor shaft. All of the operating connections and auxiliaries are placed on or above the floor level in full sight of the operator, so that any derangement of any of the working parts can be quickly observed.

The combined weight of the drum shaft with the two drums and two clutches is 300,000 pounds. The radius of gyration is 4.86 feet. The general construction of the hoist is shown in Fig. 3.

The hoist is driven by a direct-connected direct-current motor running at about 71 rev. per min. normal, which is mounted on sole plates built into the foundations. Fig. 4 shows the principal dimensions of the motor, and the heavy construction of the mechanical parts will be particularly noted. The motor is wound for 600 volts and has 16 poles. The armature is 10 ft. in diameter, the outside diameter of the frame being 14 ft. 1 in. The motor will develop 5000 h.p. for short

periods without injury and particular care is taken to build a machine that would stand high temperatures without injury. The frequency of hoisting and the duration of the hoisting period is somewhat uncertain, and as a factor of safety, mica and asbestos insulation has been used throughout the machine.

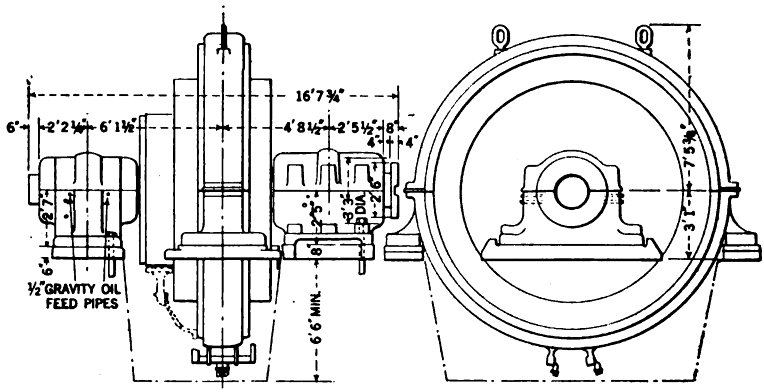


FIG. 4

The armature coils are all mica insulated and the field coils are copper strap wound on edge, with asbestos insulation. The insulation is such that an ultimate temperature of 150 deg. cent. could be carried without injury. For hoists of this size it is important to guard against failures of insulation due to temperature as the ventilation of the motor due to the periods of rest and the slow speed when running is not particularly good. The total weight of the rotating part of the motor is approximately 70,000 pounds and the radius of gyration is 4.1 ft. The motor is separately excited at 250 volts. The tests conducted on the machine show high efficiency for a machine of this type and are given in Fig. 5.

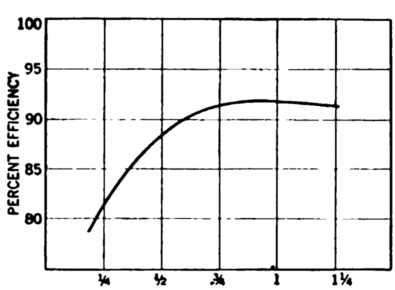


FIG. 5—EFFICIENCY CURVE OF HOIST MOTOR

The motor generator set supplying power to the hoist motor is driven by a 1400 h.p., 2200-volt, 60-cycle induction motor, 14 poles, running at a maximum speed of about 505 rev. per min. The generator is designed to deliver about 6000 amperes

during period of acceleration at a maximum of 600 volts. It is connected solidly with the motor, the control of the speed and the direction of rotation being by means of the excitation on the generator. To enable the peak loads to be satisfactorily commutated, on account of the high speed, a commutating machine with interpoles was built. The armature has a diameter of 66 in., and the field has 10 poles, so that during acceleration peak period 1200 amperes are collected by brush arm. The generator is arranged for separate excitation at 250 volts, from the direct-connected exciter. As the speed of the set varies during operation and it is desirable to maintain a constant exciter voltage, an automatic voltage regulator was installed for this purpose. Mounted between the motor and the generator is a steel plate flywheel having a diameter of 12 ft., and a weight of 100,000 pounds. The peripheral

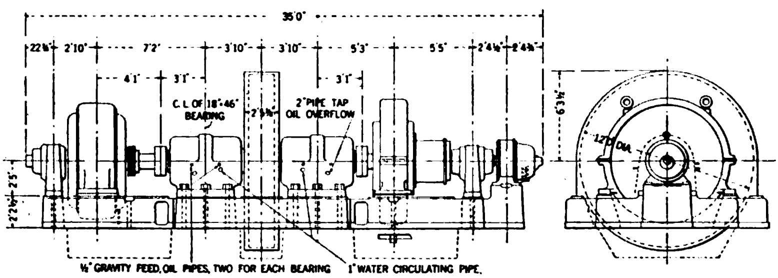


FIG. 6—FLYWHEEL MOTOR-GENERATOR SET

speed of the wheel is about 19,000 ft. per min. and it is built up of steel disks cut from solid plates, the disks being held together by rivets. The wheel is shrunk on the shaft and finished all over. It is protected by a case which completely encloses it. This case reduces the windage very appreciably and also affords mechanical protection. The flywheel is carried by two water cooled gravity feed lubricated bearings 18 in. in diameter by 46 in. long. In spite of the high bearing speed of about 40 ft. per sec., the bearings run quite cool. The flywheel and its shaft are built up as a unit, the shaft having a forged flanged coupling at each end to which motor and generator are coupled. In case any repairs are necessary to the motor or generator, the rotating parts can be removed without disturbing the flywheel. The whole of the set is mounted on a bedplate built into the foundation. The speed of the set during operation

is controlled by an automatic slip regulator which has been previously described.* The slip regulator also is used for starting the set and the input for which it is adjusted can be readily changed by varying the amount of the counterweight. As previously mentioned, the hoist operates for periods of

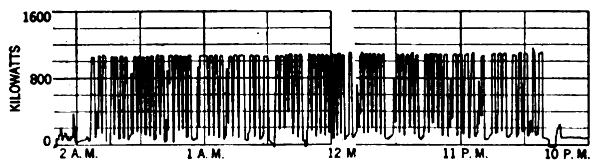


FIG. 7—WATTMETER CURVE SHOWING INPUT TO MOTOR DRIVING FLY-WHEEL MOTOR-GENERATOR SET

three or four hours at a time at full capacity and during the remainder of the time the work is decidedly intermittent.

Fig. 7 shows the input to the a-c. motor driving the flywheel set when running at regular hoisting. It will be noticed that the slip regulator limits the maximum input during each period to practically the same value, and that between trips the loads

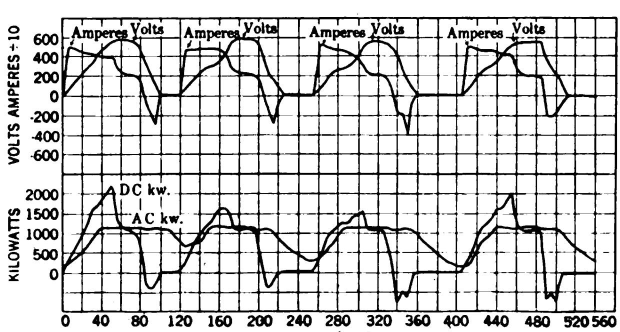


FIG. 8

drop down to practically the friction load of the set. This is due to the fact that the interval between trips is longer than is necessary to bring the flywheel up to full speed. A typical days work shows the following hoisting conditions:

A.I.E.E. TRANSACTIONS, 1911, Electrically Driven Reversing Rolling Mills, by Wilfred Sykes.

Trips hoisting ore	131
Trips hoisting waste	36
Trips with timber	13
Trips with men	18

Fig. 8 shows typical cycles when operating under present conditions. The hoist at present is working from a maximum depth of 2800 ft. and the acceleration peaks are not as high when working from 4000 ft. These curves show the direct-current volts and amperes, the direct-current kilowatt and the alternating-current input. The overall efficiency from these curves, including all mechanical and shaft losses as well as electrical losses; that is, the ratio of input to the actual work required to lift the material is 48 per cent.

It was estimated when the hoist was installed that the light-load losses would be approximately 126 h.p., including excita-

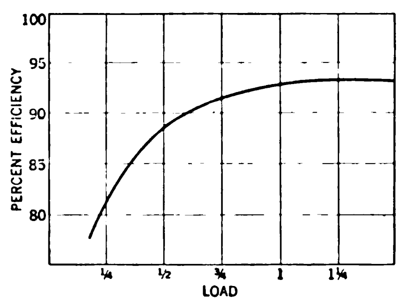


FIG. 10—EFFICIENCY CURVE OF GENERATORS SUPPLYING POWER TO HOIST MOTOR

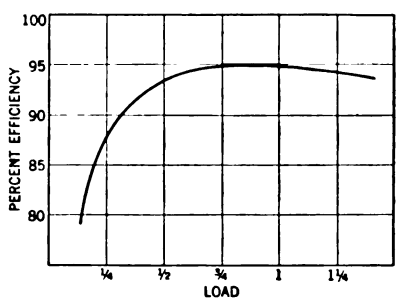


FIG. 11—EFFICIENCY CURVE OF INDUCTION MOTORS DRIVING FLYWHEEL SET

tion for the hoist motor, or in other words for the equipment in condition to start hoisting. Tests made after installation showed that these losses did not exceed the above figure and were probably slightly less. The actual input could not be determined within one or two horsepower due to variation in reading of instruments. The hoist has been in operation continuously since the middle of May and has carried the load of the new shaft and occasionally the existing shaft during the time the old steam hoist was out of commission.

This hoist is noteworthy as it is the largest electrically-operated hoist in the United States, and it marks a decided departure from previous practise in handling large quantities of ore in the metal mining fields.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 16, 1915.

RECENT IMPROVEMENTS IN THE ELECTRIC LIGHTING OF STEAM RAILROAD CARS

BY R. C. LANPHIER

ABSTRACT OF PAPER

This paper deals with the axle generator system of electric lighting for steam railroad cars, and describes recent improvements in control systems for obtaining proper voltage from the generator under all conditions and proper regulation of battery charge to conserve the life of the storage battery. Methods of control depending upon *voltage* of the battery have not been wholly successful. Since the beginning of 1914 extensive use has been made of systems of control of the battery charge based upon actual input and output in ampere-hours, and one such system, which has proved successful, is described.

In the development of the system of control by ampere-hour meter, tests were made by means of a special graphic recording ampere-hour meter which gives a complete record of the treatment received by a storage battery with any axle generator system. Actual records from long runs are reproduced, to show the results obtained in the operation of the system of control of charging by ampere-hour meter. With this system the battery has minimum work to do, in most cases operating between points of 75 or 80 per cent of full load and full charge, and the lighting load is put on the generator as much as possible.

THE PROBLEM of supplying a uniform and thoroughly satisfactory electrical illumination of steam railroad cars is much more difficult than might appear to engineers not familiar with some of the problems involved, and which do not occur in supplying electricity from a stationary plant.

Three general methods have been employed in the United States and Canada for the operation of electric lights on steam railroad cars; the method now most generally used and which will undoubtedly come into even more extensive application in the future, being that employing a generator suspended beneath the car, driven by a belt or chain from one of the car axles, and operating in connection with a suitable storage battery carried on the car to furnish a supply of current under all conditions of train operation.

The second method is the so-called straight storage method, in which each car of a train carries only a storage battery which

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is charged at certain points enroute or at terminals, from stationary charging plants, and which carries the lighting load at all times.

The third method is by means of the so-called head end system, employing a generator in the baggage car or other suitable point in the train, which may be driven either by means of a steam engine supplied with steam from the locomotive boiler, by means of a gasoline engine, or by direct drive from the car axle, in the latter case giving a system somewhat similar to the first mentioned.

With the head end system, a small storage battery is sometimes used on each car of a train, so that the lighting will be taken care of when a car is detached from the train, as when laid off at a station enroute. In other cases a battery is employed on only one or two cars of the train, acting as a reserve when the generator is stopped, but not taking care of lights on other cars of the train than those having the batteries, in case such cars are detached.

For the purpose of this paper, only the first or so-called axle generator system will be considered. There are, and have been, many more or less different arrangements of axle generator systems; that is, differing as regards the suspension and drive of the generator, its electrical characteristics, the relation of the generator to the battery, the controlling systems for obtaining proper voltage from the generator under all conditions, the methods of regulating the battery charge, of protecting the battery, of regulating the voltage supply to the lamps or other devices on the cars, etc. It is not within the scope of this paper to consider the many modifications and detail developments of axle generator systems, especially as regards the merits of the several systems of so-called constant generator current, constant battery current, constant generator potential, etc., but rather those characteristics of all axle generator systems affecting the performance and life of the storage battery used in connection therewith.

Aside from the difficulty of obtaining steady and uniform voltage and ample supply of current from an axle driven generator under the widely varying conditions of train speed, and variation of load, there has been, with all systems of electric train lighting, more or less difficulty in obtaining proper battery charge without serious overcharging or overdischarging; both of which may be considered seriously detrimental to the proper

performance of the battery and particularly to its proper maintenance and life.

As the charge and discharge of a battery connected across the generator line, as shown in Fig. 1, depends upon the terminal voltage of the generator, or more correctly, the voltage imparted at the battery terminals from the generator, it is most important that a suitable charging voltage, depending upon the state of charge of the battery, should be automatically maintained so as to charge the battery properly. With axle device equipments employing voltage method of tapering off the battery charging current, the latter is intended to remain constant until such time as a supposedly predetermined voltage is attained, when it is intended that the charging current will gradually decrease with the increasing e.m.f. of the battery.

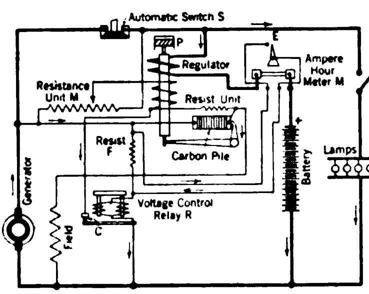


Fig. 1—Panel with Ampere-Hour Meter

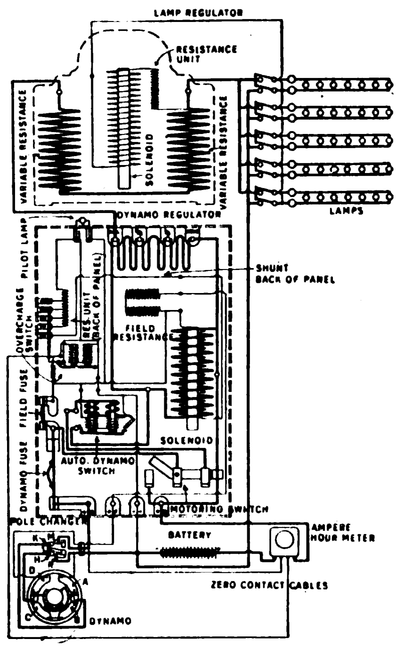


Fig. 1a—Wiring Diagram of Consolidated Axle Equipment with Ampere-hour Meter Control

With a stop charge system, the voltage of the generator should either be automatically reduced so that further charge will not be given the battery until some discharge has taken place; or if preferred, as in some systems, the generator should be automatically disconnected from the battery after the full charge has been obtained and connection should not be restored until after some discharge has taken place; but in either case, by proper control, excessive overcharge will thus be prevented. On the other hand, with any system having a control such that

the voltage of the generator is dropped below the charging voltage required for the battery before full charge has been obtained, after successive discharges a gradual reduction of charge must take place, resulting ultimately in a seriously undercharged battery with danger of sulphation, reduction in life and excessive maintenance charges, just as are the results on the other hand from overcharging, causing disintegration of plates, loss of active material, excessive gassing, unnecessarily frequent flushing, and all the resulting evils which bring about similar high maintenance charge and greatly decreased battery life. Manufacturers of electric car lighting systems have devoted great inventive ability and large expenditures to the development of details of control for axle generator systems, in an effort to prevent battery troubles, as referred to, and to a degree have been successful, but all methods of control depending upon voltage of the battery, must in the last analysis fail to a greater or less extent because of the inherent characteristics of a storage battery as regards voltage of charge and discharge under varying conditions of temperature, age of plates, condition of battery resulting from rate of charge, and other factors familiar to battery engineers.

The very important effect of temperature on the charging voltage of a battery is clearly illustrated in Fig. 2. If the battery is cold the voltage on charge may follow the curve *A* which is slightly higher than normal, and requires a maximum voltage at the finish of several volts above normal.

On the other hand, if the battery is comparatively warm and the plates in good condition, the charging voltage will follow the curve *B* which is somewhat below normal, and the gasing voltage may be considerably below the gasing voltage of the battery under normal conditions. If the charge is continued the battery warms still further and the voltage actually falls further away from the normal maximum.

When the specific gravity ceases to rise it may be taken as a sure sign that the battery is fully charged. This point is indicated by a cross on the specific gravity curve. This is after approximately 10 hours charge, but it should be noted that the voltage curves have reached their maximum value some time previous to this.

The curve *A* has reached its gasing voltage after 8½ hours charge, while the curves *B* and *C* show that even a normal or a warm battery rises to a gasing voltage before the charge is fully completed.

The charging voltage of a storage battery will vary anywhere between the two dotted curves *A* and *B*, and it will rarely, if ever, follow the ideal charging curve *C*.

With a stop charge system, depending upon voltage, this has usually been set high, for 40 or 42 volts, in order to insure that the storage battery gets sufficient charge. With a warm battery, or in many cases, even with a battery under normal conditions, the charging voltage may ***never*** reach this point and a long continued overcharging results, which boils out active material and causes excessive growth.

If the relay is set so as to accommodate a low battery voltage, it will cut off under normal conditions *too soon* and leave the battery in a half charged condition.

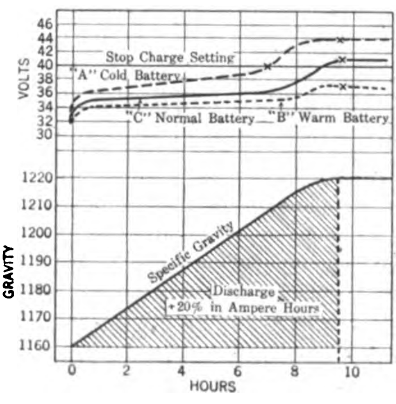


FIG. 2

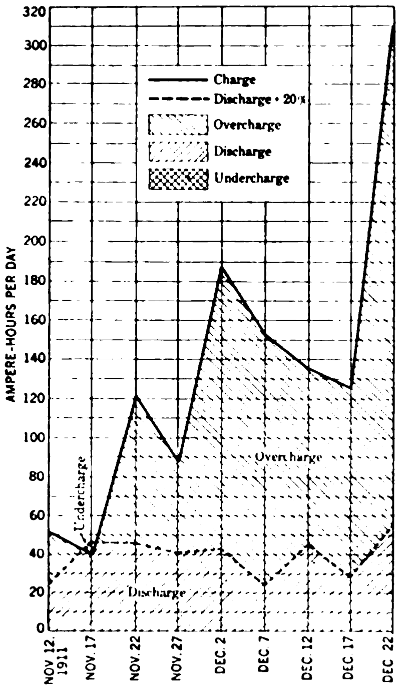


FIG. 3—CONDITION OF AXLE EQUIPMENT SHOWN BY AMPERE-HOUR METER TEST

From the diagram and the above description, it will readily be seen that it is practically impossible to set a stop charge voltage relay for any definite voltage, so that it will meet the ordinary variations in battery condition and give a satisfactory percentage of overcharge without, on the other hand, rendering the battery liable to undercharge.

In Fig. 3 are shown the actual results of test on a battery operating with axle generator equipment on a well known rail-

road system, from which it will be noted that during the period of this test an average overcharge of 100 ampere-hours per day was given the battery; that is, 5 hours of continuous boiling on overcharge at 20 amperes per day. It requires no argument to show that a battery subjected to such conditions will rapidly disintegrate, showing excessive maintenance cost and short life.

For the purpose of showing results that have been obtained by the application of a control of the battery charge based upon actual input and output in ampere-hours instead of by voltage, one well known system will be referred to, although it should be understood that the fact that this particular system is considered, does not mean that other systems now in general use are less or more subject to battery troubles from improper control by the voltage method, than this particular system.

In the control of any axle generator system it is necessary to have some type of rheostat in the generator field circuit operated by devices automatically responsive to changes in the load current and the voltage across the battery terminals, so that with varying train speeds and varying load, the field of the generator will be automatically varied to maintain a practically constant voltage while the battery is charging; and a lower but practically constant voltage when the battery is floating, in those systems where the generator is not disconnected from the battery and load line after the battery has reached full charge.

In addition to the controlling rheostat for the generator field, practically all axle generator systems also have a "drop-out" switch, as it is usually called, which automatically connects the battery and load line to the generator after the train has reached a certain critical speed; usually 12 to 15 miles per hour and which disconnects the generator from the line when the speed drops below a certain rate; usually 8 or 10 miles per hour, as the voltage of the generator then drops below the normal discharge voltage of the battery.

Outside of these two main elements for generator control, all axle generator systems now used in this country also have a lamp regulator or rheostat automatically responsive to changes in voltage from the generator and battery and to changes in the lighting load of a car, designed to maintain a uniform and steady voltage on the lamps. The lamp regulator and the

performance of the several types thereof now in use, is not directly related to the problem of battery control, but it may be stated, in passing, that a great amount of effort and ingenuity has been expended in the design and construction of lamp regulators and there is still room for improvement in the way of simplicity of design and smoothness of operation, so as to avoid any flickering or variation of the lights with the starting, stopping and sudden variations in speed of a train.

Aside from the generator field regulator and automatic or drop-out switch, certain other features in the way of relays and resistances are required for generator control, and in the system above referred to, illustrated in Fig. 4 as designed for voltage control of the battery, the relay responsive to the voltage across the battery is shown at *R*. In this system, as shown in

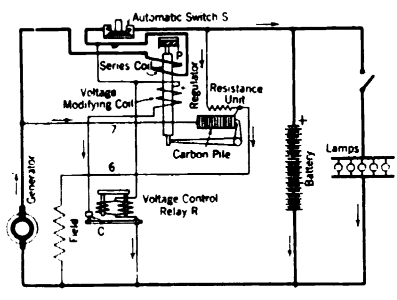


FIG. 4—PANEL

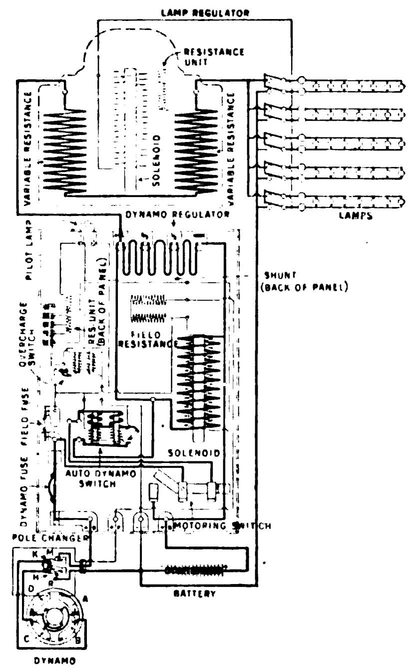


FIG. 4A—WIRING DIAGRAM OF CONSOLIDATED AXLE EQUIPMENT

Fig. 4, the regulating solenoid acting on the carbon pile comprising the resistance in series with the generator field, is arranged so as to maintain a proper charging voltage, say 43 to 44 volts at the generator terminals, until the voltage of the battery has risen sufficiently high to lift the armature of the relay *R*, when circuit is closed through the contact *C*, thus increasing the flow of current in the potential winding of the solenoid controlling the carbon pile, decreasing the pressure on the pile, reducing the field excitation of the generator, and thus dropping the

voltage of the generator so low as to cause a large reduction in the energizing effect of the potential winding of the drop-out switch *S*. With this condition and a slight reversal in current flow through the series winding of the drop-out switch, due to current passing from the battery back to the generator, the automatic switch will drop out, disconnecting the generator, thus causing the battery to carry the load until such time as the train has slowed down to a very low speed or has stopped, when the relay *R* will be de-energized, breaking circuit to the shunt winding of the regulator solenoid, and restoring the entire system, so that on starting of the train and reaching critical speed, the generator will operate at charging voltage until such time as the battery has again become fully charged according to voltage.

Somewhat similar control hasbeen employed in other well-known systems of electric railway train lighting, and while in many respects satisfactory, particularly with a new battery operating at fairly uniform temperature, none of these systems has given the results obtained with a control based upon ampere-hour input and output of the battery, in other words, on the battery's actual quantitative performance.

Something over two years ago, several railroad companies operating electric lighted cars, applied ampere-hour meters in an experimental way in connection with existing systems, substituting the full charge contact in the ampere-hour meter either in place of the contact operated by the voltage relay, or in connection therewith, so as to make the termination of charge to the battery dependent upon its condition with respect to charge as indicated by the ampere-hour meter. Preliminary results were quite satisfactory, but the ampere-hour meter was not extensively employed for automatic control of battery charge with axle generator systems until the beginning of 1914 when the Pullman Company applied meters on a number of cars. The application of the meter to the system already referred to, and as shown without the meter in Fig. 4, is illustrated in Fig. 1, the meter being shown diagrammatically at *M*. This entire diagram, like Fig. 4, is schematic, small details and structural features being omitted for the sake of simplicity.

Following results in the way of improved battery maintenance, which is by far the largest item in the cost of maintaining axle generator systems, meters were put on a large number of cars owned by the Pullman Company and at the present time prac-

tically every electric lighted Pullman car is thus equipped. Before describing in detail some of the tests that have been made and results obtained, it may be of interest to mention briefly the type of meter which has been used for this work.

The ampere-hour meter employed is of the mercury motor type, having a copper disk immersed in a mercury chamber formed of suitable insulating material, and with current led into and out from the mercury at diametrically opposite points so as to pass across a diameter of the disk. The current is subjected to the action of a field on each side of the center of rotation, produced by a powerful permanent magnet, so that the torque imparted to the moving system is proportional to the current flow through the copper armature, irrespective of voltage.

By means of a device termed a " variable resistor " connected in parallel with the motor element and mercury chamber of the meter, and both across a shunt of suitable capacity in the load line, the ratio of current sent through the armature with respect to the total current in the line is varied between charge and discharge, so as to give a lower speed to the meter on charge, for any given line current, than on discharge, thus enabling automatic compensation to be made for the inefficiency of the battery, as is necessary in order that the meter may correctly maintain the battery in properly charged condition. By means of a suitable adjusting device for varying the effect of the resistor element, any desired percentage of overcharge may be given, but in railway train lighting work it has been found desirable to give an overcharge with lead storage batteries of about 25 per cent and with Edison batteries, of about 30 per cent. The ampere-hour meter can readily be set for either percentage, and in fact for any desired percentage, according to the age of the battery, conditions of temperature and other factors which may affect the overcharge required. It is important to note, however, that even should the overcharge given the battery be 5 or 10 per cent greater than necessary to keep it in fully charged condition, the total overcharge that a battery in train lighting service will receive is so little as compared with the total ampere-hour input and output over an extended period, that practically no deterioration will be caused as compared with the enormous overcharge which may easily be obtained with a very slight variation in the charging voltage, when the control of charge is dependent upon voltage.

The ampere-hour meter as described above is provided with

suitable contact at the zero or full charge point on the dial, the hand moving clockwise on discharge and counter-clockwise towards zero on charge. The zero contact of the meter is shown diagrammatically at *E* in Fig. 1 and it will be seen that the contact is connected across resistance , *F* in series with the winding of the voltage relay so that the closing of the contact will immediately increase the energizing effect in the relay, causing it to close circuit through contact *C* thus increasing the current in the shunt coil of the field controlling solenoid *P*, which finally causes a decrease in the pressure on the carbon pile, a consequent decrease in the energizing effect of the generator field, and a reduction of the generator voltage to floating voltage of the battery.

As the floating voltage of a storage battery is far more constant than the voltage of charge or discharge under widely varying conditions of temperature age, etc., it is possible to determine a floating voltage such that the battery will receive a negligible charge or give a negligible discharge, outside of that required for any lamp load that may be on when the generator is brought to the floating voltage as predetermined, and which is dependent upon adjustment of the several resistances in the system including *M* and *G* as shown in Fig. 1.

For sixteen cells of lead battery, as regularly employed with all axle generator systems at this time, a floating voltage from 34 to 35 volts has been found thoroughly satisfactory, giving a minimum charge or discharge from the battery. In the operation of the systems as shown in Fig. 1 with the ampere-hour meter as control, it will be noted that after contact has been closed at full charge point operating the relay *R* and reducing the generator to floating voltage, the battery will discharge and carry any load that may be on in the car, as the relay *R* will remain closed after its armature has been drawn up, even with the reduced voltage across the generator terminals. This condition will continue until the next stop of the train is made or until a very low running speed has been reached, when the armature of the relay *R* will drop out, thus restoring the conditions existing before full charge had been reached and permitting the generator to operate at charging voltage after the train has started up and passed above the critical speed of 12 to 15 miles per hour. Charging will then begin and continue until the battery has again reached full charge as shown by the ampere-hour meter, when operation through the relay to bring the generator to floating

voltage will again take place. With this method of operation the battery will receive a proper overcharge without any serious and destructive overcharges, and will at all times, except in case of a very long accidental stop while lights are being used, have practically full charge, so as to operate at highest efficiency and give a most uniform supply of current for the lighting load. On the other hand, with this method of operation the battery has minimum work to do, in most cases operating between points of 75 per cent or 80 per cent of full load and full charge, and the lighting load is put on the generator as much as possible, which has not always been the case with the systems of voltage control where it was frequently the case that the battery would work over a very wide range, carrying the load a great part of the time when the generator should have done so. It is obviously far less expensive to carry the lighting load on the generator than to use up battery life, when the train is operating at such speed and under such conditions as to permit the generator doing the work instead of the battery.

In Figs. 5 and 6 are shown two sections of curves from recording ammeters and voltmeters obtained on a Pullman car operating on a large and well known railway system of this country. In these figures and from the notations subjoined to them, will be seen the remarkably uniform results in battery operation obtained by the application of the ampere-hour meter control. The generator operates at charging voltage only sufficiently long to restore charge to the battery after each period of running below critical speed or stopping; and during the period of floating, the charge or discharge of the battery is practically negligible.

It will also be noted from Fig. 7, showing a graphic record of generator output in watts with this method of control, that the generator is carrying the lighting load during the greater portion of the time that this load is on, and during the balance of the time, in the early morning and daylight hours, the generator is very lightly loaded, as the battery is floating, practically no lighting load is on and there is thus a great economy in power consumption by the several generators on a train, as well as the improved battery maintenance already referred to. This consideration alone is of great importance to railroad companies, as it is well known that the total consumption of energy for 10 or 12 axle generators, as on almost any through train, amounts to a large amount in dollars and cents in the course of a year. With methods of voltage control as formerly used, it would have been

simply impossible to get a curve of operation duplicating or approaching those shown in Figs. 5, 6 and 7.

In the course of the experiments conducted by the Pullman Company and several railroad companies during the past year

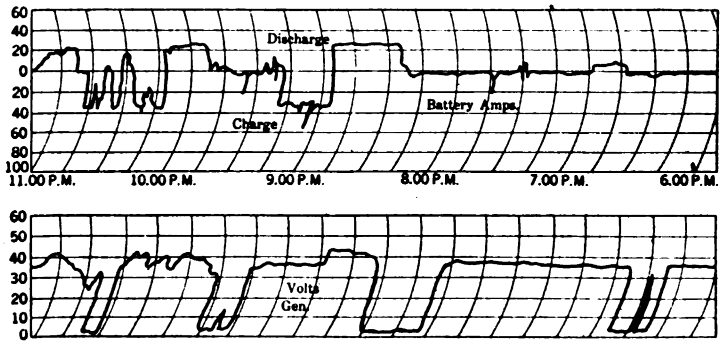


FIG. 5

to determine the conditions of battery operation before and after adoption of control of charge by ampere-hour meter, an interesting type of graphic recording meter was especially developed, this being a graphic ampere-hour meter, as shown in Fig. 9 with cover removed.

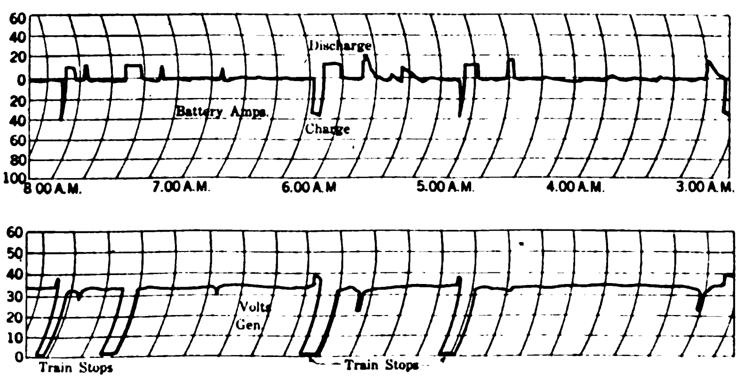


FIG. 6

This instrument is of particular interest, inasmuch as the graph is of an integrated function instead of an instantaneous or momentarily varying value. The record is obtained, as clearly indicated in the cut, by means of an ampere-hour meter suitably

connected through a driving chain to a pencil, *B*, moving across the paper chart and with another stationary pencil, *C*, arranged to be moved momentarily crosswise to a slight extent at half hour intervals, from the clock below, which also drives the paper roll. The meter as thus arranged gives a complete and definite record of the treatment received by a storage battery with any axle generator system, the chart being a cumulative record of the total battery input or output in ampere-hours, having the meter adjusted for any percentage of overcharge which it is desired to adopt during the period of test. Some results on equipments with and without the ampere-hour meter control are shown in Figs. 10, 11, 12 and 13.

Fig. 10 shows the record of battery charge and discharge on a car running between Boston and Chicago. It will be noted that when the car is not in motion the graph of the recording pencil is light, but as soon as the car begins to move, whether the equip-

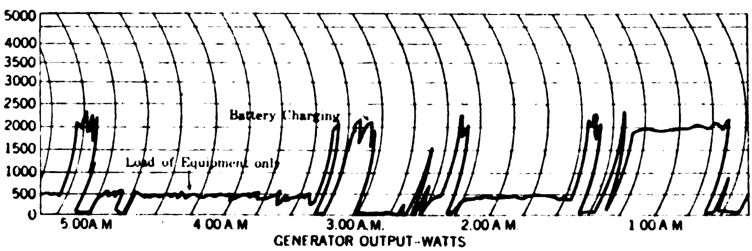


FIG. 7

ment is generating or not, the line becomes heavy. In this way practically all of the stops are indicated.

The base line has no reference whatever to the battery capacity scale, but simply gives a base line from which values of charge and discharge can be measured. For the sake of illustration, we have assumed in the curve, Fig. 10, that the capacity of the battery when fully charged, as it was from 7:00 p.m. to the end of the run, is 320 ampere-hours. Since 1/16 of an inch equals 10 ampere-hours the vertical scale can easily be figured and we have placed this scale at each end of the curve. The curve as recorded by the meter, however, is simply the two heavy lines shown. In making the zinc etching the curve has been reduced to about half size.

Fig. 10 shows that while standing in the yard there was a capacity of 215 ampere-hours in the battery. The run to the station

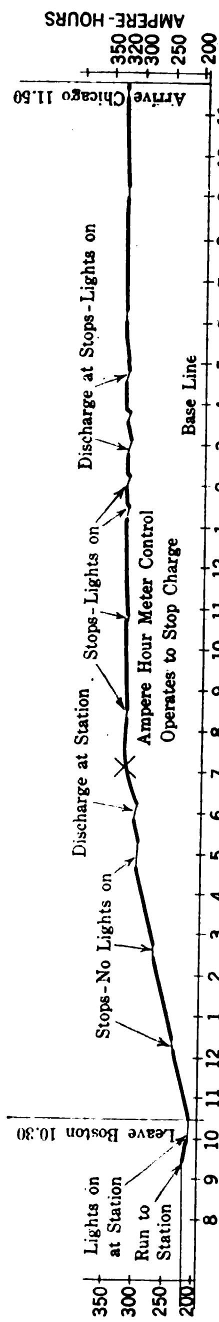


FIG. 10—GRAPHIC AMPERE-HOUR METER CHART SHOWING PROPER OPERATION OF EQUIPMENT RUNNING BETWEEN BOSTON AND CHICAGO. HEAVY SECTION OF CURVE IS CAUSED BY VIBRATION DUE TO MOVING TRAIN. LIGHT SECTIONS OF LINE INDICATE STOPS

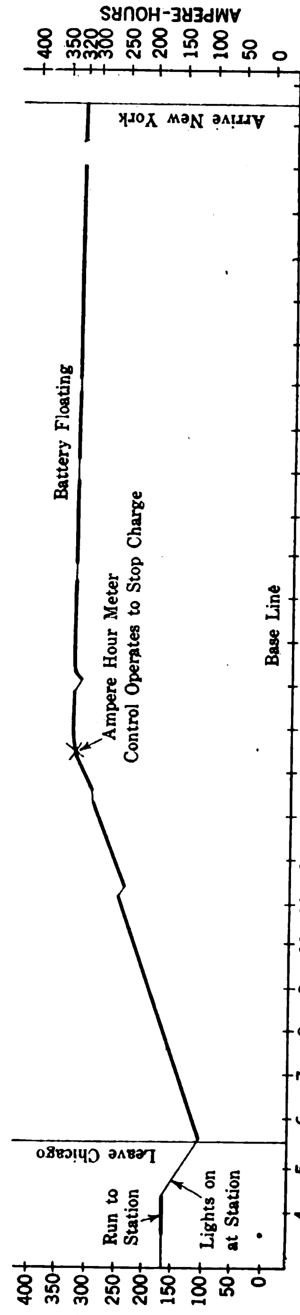
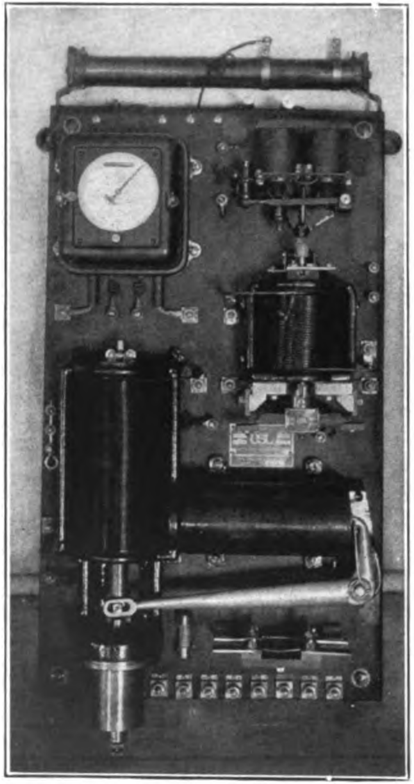
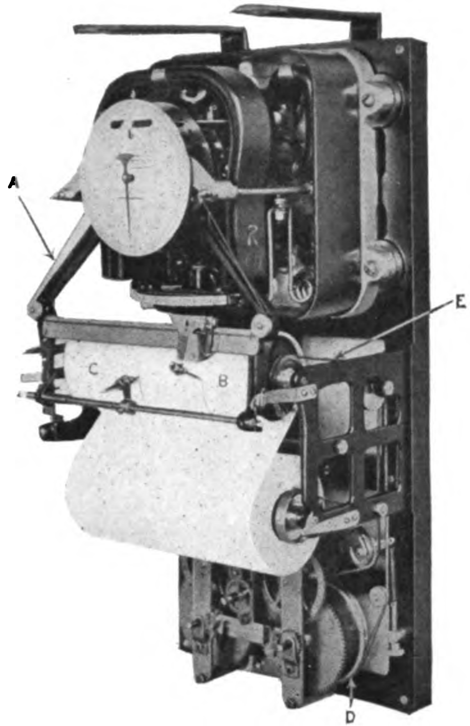


FIG. 11—ANOTHER GRAPHIC AMPERE-HOUR METER RECORD SHOWING PROPER OPERATION OF THE EQUIPMENT ON RUN BETWEEN CHICAGO AND NEW YORK. HORIZONTAL SECTION OF THE LINE INDICATES BATTERY FLOATING AT FULL CHARGE



[LANPHIER]
FIG. 8—STANDARD PANEL WITH AMPERE-HOUR METER CONTROL



[LANPHIER]
FIG. 9—GRAPHIC AMPERE-HOUR METER WITH CASE REMOVED, SHOWING RECORDING PENCIL (*B*) MOUNTED ON ROLLING CARRIAGE MOVED HORIZONTALLY BY AMPERE-HOUR METER GEAR TRAIN

is shown by the heavy horizontal line and discharge now begins as shown by the downward curve of the line. Altogether enroute to and at the station the battery discharged 10 ampere-hours. As soon as the train left the station the battery started to charge and this is indicated by an upward slope of the line; since this equipment was set for constant battery current regulation, the upward slope of this line is always at the same angle. If this had been a constant generator current regulator this degree of slope would have varied, depending upon the charging current rate.

It will be noted that at the stops during the day there was no discharge and the light lines, indicating stops, are horizontal. After sunset, however, it will be noted the light lines at all stops slope downward, this indicating a discharge at each stop. As soon as the equipment begins to generate again, however, the curve again begins its upward slope, indicating that the battery is charging at the constant rate of the regulator setting. It will be noted that at 7:00 p.m., indicated by a cross on the curve, Fig. 10, the battery has reached a full state of charge, and since this equipment was controlled by an ampere-hour meter of the variable resistor type, this meter, like the graphic meter, indicated a zero discharge and thereupon closed its zero contact, which stopped further charging of the battery. The battery then simply floated on the line, the generator carrying the load of whatever lamps happened to be in use at the time. It will be noted that there are various stops where a slight discharge occurred, but this was quickly replaced by normal operation of the equipment and the controlling meter again operated to stop further charge when the discharge plus 25 per cent had been put back into the battery.

Fig. 11 is another curve which shows the operation of an axle generator car lighting system with the generator regulator adjusted so as to provide constant battery current; the charge given the battery is controlled by an ampere-hour meter of the variable resistor type. As in Fig. 10 we find a very normal condition of affairs with the battery charging normally enroute, a few short discharges at stops, and finally coming to a state of full charge at 2:30 a.m., when the controlling ampere-hour meter operated to stop further charge, and so protect the battery from excessive overcharge. In Fig. 12 however, both the controlling ampere-hour meter and the voltage regulating solenoid were purposely cut out of service and the equipment operated as on

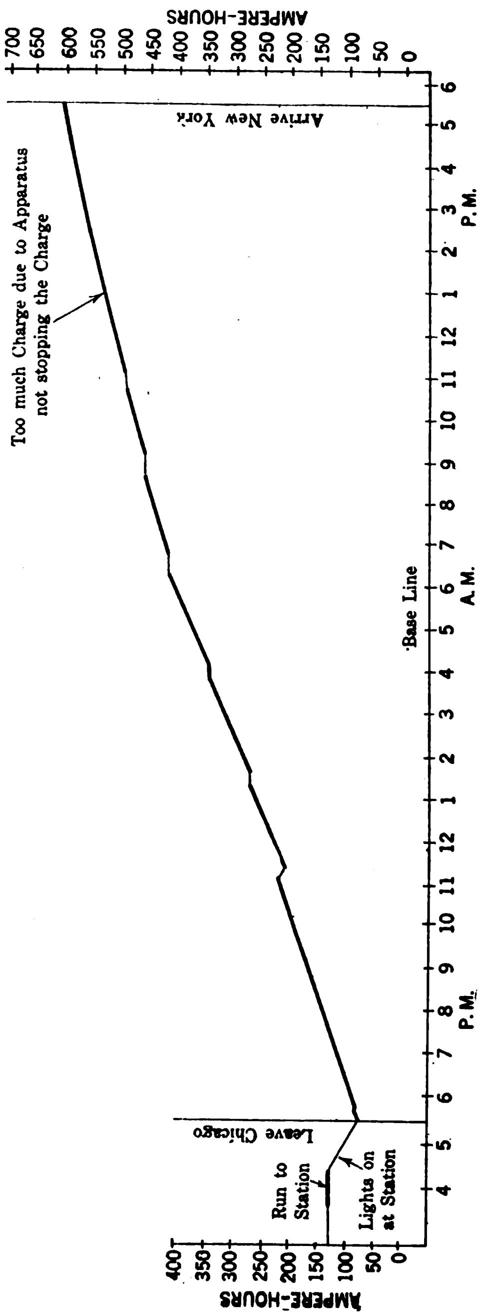


FIG. 12—GRAPHIC RECORD SHOWING THE OPERATION OF SAME EQUIPMENT AS FIG. 11, BUT WITHOUT AMPERE-HOUR METER OR VOLTAGE CONTROL OF CHARGE

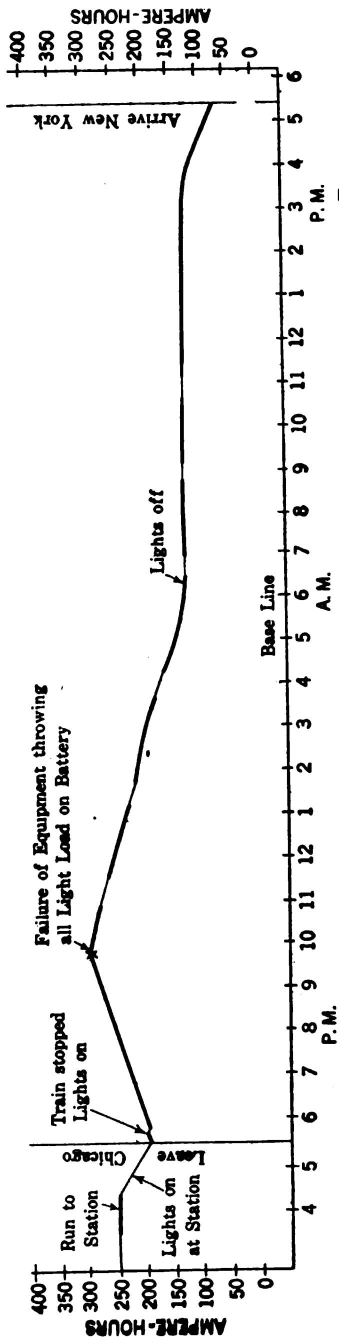


FIG. 13—GRAPHIC RECORD SHOWING OPERATION OF SAME EQUIPMENT AS FIG. 11, INDICATING A FAILURE OF THE GENERATOR EQUIPMENT AT THE POINT MARKED

a simple constant battery current control. This illustrates, of course, only abnormal conditions such as would be experienced in using a regulator of the constant current type without auxiliary control of charge, or when the voltage regulating feature of the combination current-voltage regulation of equipments with the ampere-hour meter control failed to work. In this run it will be noted that a charge of 525 ampere-hours was given a 320-ampere-hour battery which at the start showed only a 245-ampere-hour discharge. This indicates an overcharge of (280 plus 25 per cent or) 350 ampere-hours, representing the full normal charging rate for nearly nine hours on this single run. When considering the effect of such serious overcharging on a battery it is not surprising that the average battery life in car lighting service has been so small in past years before the use of voltage regulators, giving a taper charge, or the controlling ampere-hour came into use.

Fig. 13 shows another abnormal condition wherein the equipment failed to generate at the point marked " *X* " on the curve due either to lost belt which was not replaced or trouble in the equipment. It will be noted that there is a continual discharge on the battery from this point till the end of the run; this does not follow a straight line, but tapers more to the horizontal as the number of lamps in use is reduced.

From the information obtained by the graphic ampere-hour meter as illustrated in these curves, it is quite evident that a greatly reduced battery maintenance and a vastly increased battery life—the two greatest items of cost in the operation of electric lights on steam railway cars—may well be anticipated as a result of the application of control of charge by ampere-hour meter, operating in connection with existing axle generator systems; and as improvements or modifications of these systems are developed, it will probably be the case, as is already true of two well-known companies manufacturing such equipments, that the ampere-hour meter control will be adopted as standard. Now that electric lighting of steam railroad cars has become universal, or at least universally desired, anything which tends to improve the uniformity of lighting and efficiency of such systems and to reduce the expense of operation cannot be neglected by engineers interested in this branch of the electrical art.

To be presented at the Panama-Pacific Convention of the American Institute of Electrical Engineers, San Francisco, Cal., September 17, 1915.

THE AUTOMATIC SWITCHBOARD TELEPHONE SYSTEM OF LOS ANGELES, CAL.

BY W. LEE CAMPBELL

ABSTRACT OF PAPER

This paper narrates some of the history and describes the present automatic switchboard telephone system in the City of Los Angeles.

It describes how the system, which began to give service with one manual switchboard in the year 1902, has gradually been extended and transformed through several interesting stages of combined automatic and manual operation, until it now comprises 15 automatic offices and a traffic distributor switchboard which serve a total of 60,000 subscribers stations—the largest automatic switchboard system in the world.

The layout of central offices in the present plant is shown in contrast with the layout of offices in the Bell telephone plant of approximately the same size, operating in the same city.

The traffic distributor switchboard used for handling the outgoing calls from a large number of private branch exchange switchboards is the largest board of the kind in operation, includes thirty operators' positions and handles a heavy traffic. A general explanation is given of the equipment of the board, methods used in operating it and of the economies realized by means of it.

Specially interesting and important features in handling the telephone business of a large metropolitan area like Los Angeles are the methods used in caring for calls for time and for information concerning subscribers' numbers, addresses, etc., and for answering subscribers' complaints and calls for long distance connections. All of these methods are discussed at some length.

The paper closes with a concise statement of the practise of using standards of adiustment and performance for securing uniformly good service from the automatic apparatus scattered over this area of about two hundred square miles and handling from 500,000 to 600,000 calls each week day.

ALTHOUGH telephone plants using automatic switchboards are now scattered through nearly all of the civilized countries of the world, and are yearly increasing in number, they are still a novelty to many electrical and some telephone engineers. It is thought, therefore, that a description of an automatic system serving a large metropolitan area like that of Los Angeles, California, may prove of interest.

The automatic telephone system, owned and operated by the

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Home Telephone & Telegraph Company in the city of Los Angeles, is remarkable in several particulars.

1. Starting as a manual switchboard system, it has passed through several interesting stages of combined Automatic and manual operation.

2. It has had an extremely rapid growth, in order to keep pace with the growth of the city.

3. It is now the largest plant operating in competition with the Bell System.

4. It is the largest automatic switchboard plant in the world.

5. It embodies the largest and busiest semi-automatic switchboard of the traffic distributor type.

6. It includes an unusually large number of private branch exchanges for a plant of its size.

Early History

The Home Telephone & Telegraph Company began service in 1902 with a manual system using a common-battery, two-wire-multiple switchboard with an ultimate capacity of 18,000 lines, of which 7000 were at once to be put into service. This board was at that time the very latest development in manual telephony and it was supposed that it would take care of the "independent" telephone service in Los Angeles for some time to come. But the officers of the company had greatly underestimated the requirements, for the subscription list grew so rapidly that within two years after the beginning of service 10,000 lines were in use and the demand for service was so great that it became evident that only the business district and a portion of the residence district in the south and west sections of the city could be accommodated by the equipment. .

In those days of comparatively small telephone plants, engineers of "independent" telephone companies generally felt that all subscribers' lines in each city should be connected to one switchboard or at least to one central-office, but the engineers of the Los Angeles company soon concluded that the cost of connecting all lines in that rapidly growing city to either one switchboard or one central-office would be prohibitive. It was, therefore, decided to build a branch office in the south end of the city and thus relieve the main office of about 2000 lines. The building was erected with a view of installing manual equipment, but after investigating the successful automatic telephone

systems at Grand Rapids, Michigan, Dayton, Ohio, and other cities, the officers and engineers of the Home company decided that the automatic system was what they needed and adopted it.

The plant agreed upon was, briefly, that the original office was to remain, for the time being, a manual office and was to serve directly only the business portion of the city, while central offices equipped with the automatic system were to be scattered over the city to give service in the outlying districts, and were to interconnect with Main, the centrally situated manual exchange.

First Automatic Central-offices. The first of the automatic

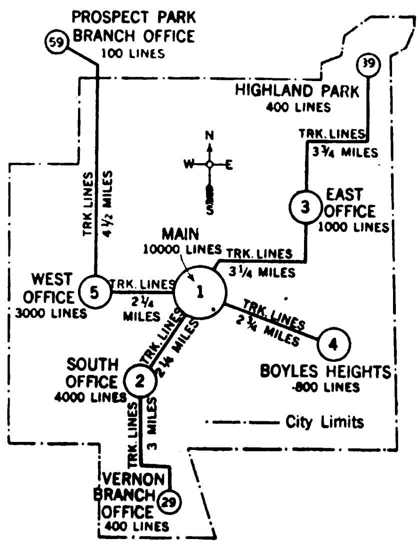


FIG. 1

exchanges, known as South, and equipped for 4000 lines, was completed in July, 1904, and was quickly followed by four additional exchanges: Boyle's Heights with 800 lines, East with 1000 lines, Vernon with 400 lines, Highland Park with 400 lines, Prospect Park with 100 lines, and West with 3000 lines. Consequently, by the latter part of 1905, the system had developed as represented by the diagram in Fig. 1.

The use of seven offices in a system serving but 19,000 ines was regarded as very bad practise, even by many of those engineers who at that time had progressed beyond the single office idea; but experience has justified the plan, because the

great territory to be covered, as shown by the distances in Figs. 1 and 16, together with the enormous growth in population and the corresponding growth of telephone stations, as shown by the curves in Fig. 2, have made a comparatively large number of offices necessary in order to keep the cost of the outside plant within reasonable bounds. In Fig. 2 the ratio of curve *A* to curve *B* is 10 to 1, and the curves, therefore, show in a striking way how very closely that ratio between population and the Home Telephone Company's instruments has been maintained.

The special suitability of automatic equipment to such a multi-

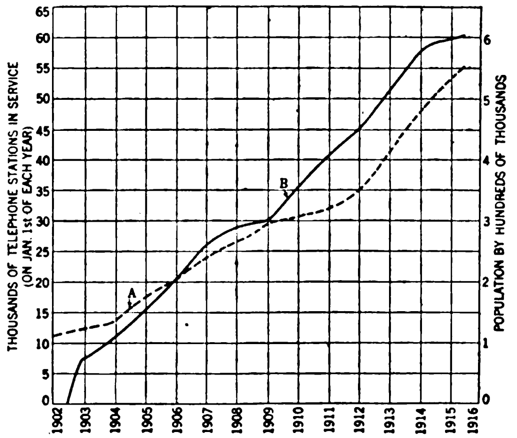


FIG. 2—CURVE *A* SHOWS GROWTH OF POPULATION OF CITY OF LOS ANGELES FROM 1902 TO 1915, AND CURVE *B* SHOWS THE GROWTH BY SUBSCRIBERS' STATIONS OF THE HOME TELEPHONE AND TELEGRAPH COMPANY FOR THE SAME PERIOD

office system is fully explained in a paper presented by the writer before the Institute in 1908.

Type of Apparatus Used. It is deemed worthy of note, in passing, that in order to secure the advantages of the automatic system the Home Company had to take a very decided step backward in one particular, *i. e.*, all of the larger manual switchboards then being made, were of the common battery type, while the only automatic telephones available were of the older local battery type (see Fig. 3). During more recent years the automatic switchboards first installed in Los Angeles have all been remodeled to give common battery service, and many of the wall instruments have been remodeled into a smaller type similar

FIG. 3 [CAMPBELL]

FIG. 5 [CAMPBELL]

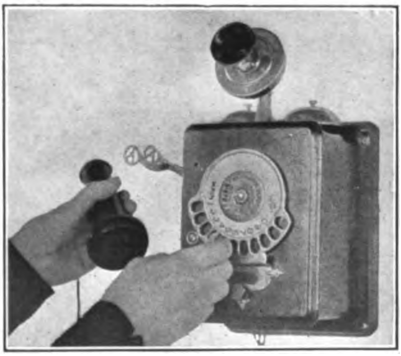


FIG. 4 [CAMPBELL]

FIG. 6 [CAMPBELL]

to that illustrated in Fig. 4. The type of desk instrument used is shown in Fig. 5. The original apparatus required a calling party to push a button on his telephone to ring the called party, but recently much of the equipment has been remodeled to automatic ringing.

While the telephone instruments used in Los Angeles are all of the "three-wire" type and are somewhat less attractive in appearance than those of the latest "two-wire" type, the service given to the subscribers is practically the same as that rendered by the latest automatic apparatus and is, at least, as well liked as that which the competing company is able to supply with modern, well operated manual switchboards.

Fig. 6 is a view of the switchboards, for serving 4000 lines, as originally installed in the South office in 1904. This was before the days of Keith line switches and each line, therefore, terminated in a Strowger type first selector. Each of the ten racks in the thousand line group in the foreground of Fig. 6, carries one hundred first selectors, ten second selectors, ten third selectors and ten connectors. The functions of these switches have been explained in previous papers, and while brief mention will be made here of the method pursued in setting up connections between the automatic offices, it is felt that more interest will center in the methods of inter-connecting between the one manual office and the automatic offices.

The Numbering Scheme. Before explaining the system of calling, the numbering scheme should be outlined. All numbers used for complete automatic connections in Los Angeles had five digits.

As indicated in Fig. 1 the South office is the "2" office, *i.e.*, it was arranged to accommodate the numbers from 21,000 to 28,999, of which the numbers from 21,000 to 24,999 were then used.

Vernon is a branch of South and was designed to accommodate the numbers from 29,000 to 29,999, of which the numbers 29,000 to 29,399 were in use.

The East exchange was designed to accommodate the numbers from 31,000 to 38,999, of which the numbers from 31,000 to 31,999 were in use.

Highland Park is a branch of East and used the numbers 39,000 to 39,399.

Boyle's Heights used the numbers from 41,000 to 41,799.

West used 51,000 to 53,999.

Prospect Park, a branch of West, used the numbers from 59,000 to 59,099.

Inter-Connections between Automatic Offices. When setting up connections with apparatus of the early Los Angeles type, the first selector responds to the first movement of the dial and selects a trunk line to the exchange corresponding to the first digit of the number being called. A subscriber, for instance, of South office (the 20,000 exchange) calling 2 as the first digit, will select a local trunk line in South office; if he calls 3, he will select an inter-office trunk to East office (the 30,000 exchange) or if he calls 4 he will select a trunk to Boyle's Heights office (the 40,000 exchange). The second turning of the dial actuates the second selector to pick out the thousand group in the exchange or its branch office. The third movement in like manner picks out the hundred. The fourth and fifth movements pick out respectively the tens and units on the connector switch. Suppose now a subscriber in the South office wishes to call No. 39,143, which is in the Highland Park office. The first movement of the dial operates a first selector in the South office which selects a trunk line to East office. The second movement is utilized in the East office by a second selector which extends the connection over a trunk line to Highland Park office where the call is completed in the regular manner, by a third selector and a connector. Impulse repeaters were used on the inter-office trunks as in present practise.

Automatic to Manual Connections. Any automatic subscriber wishing to call a number in the manual district turned his dial from finger hole 1 which was marked *MAIN* on all dials (see Fig. 3), and pressed the ringing button; this operated a first selector which selected a trunk line ending in a cord and plug on the Main office switchboard and signaled an A operator, who, by throwing a key, put out the signal light and connected herself with the automatic subscriber. Then, ascertaining the number wanted, she plugged into a multiple jack of the called line and rung the subscriber. When the calling subscriber hung up his receiver the first selector released, freeing the trunk, and when both subscribers had replaced their receivers, supervisory lamps gave the disconnect signal to the operator. Each operator handled thirty trunks, to which six hundred automatic subscribers had access.

A connection of the character just described is illustrated in Fig. 7.

Manual to automatic connections. Besides the twelve incoming trunk positions at Main office, there were four outgoing trunk positions and a trunk multiple which enabled any operator in Main office to trunk a call to an outlying office. When a manual subscriber wanted to call an automatic number, say 24,425, which is in the South exchange, he removed his receiver from its hook and asked central for the number. The operator used an order wire to repeat the number to an operator

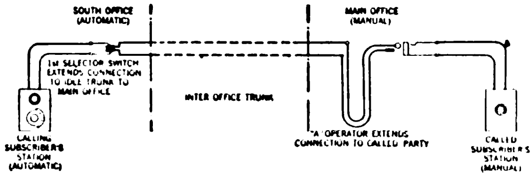


FIG. 7—CONNECTION FROM SOUTH OFFICE TO MAIN

at a switching section or B board in the South office, who assigned a trunk line, put up the connection and rung the subscriber. Both operators had double supervision, that is, they could tell when either or both subscribers hung up their receivers. At the automatic end, in the South office, the switching or manually operated B board was used for handling trunk calls from Main only and the lines from all automatic subscribers to the exchange were multipled through it. There was

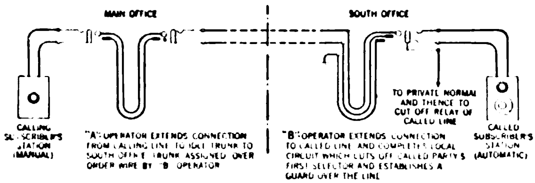


FIG. 8—DAY CONNECTION FROM MAIN TO SOUTH

a busy test so that when an operator had made a connection to an automatic line, it could not be called by an operator at another position or by another automatic subscriber, and *vice versa*, when a connector switch had completed a connection to any line, that line tested "busy" to the B board operators.

Such a connection from the manual office to an automatic office is illustrated by the diagram in Fig. 8, and is evidently in conformity with regular manual practise, with the added feature of the inter-working busy test in the automatic office.

B boards of the character outlined were installed in South, West, East and Boyle's Heights offices, but calls to Highland, Vernon and Prospect Park were handled automatically from the four outgoing trunk postions at Main. These positions were used, also, to call into the larger automatic offices at night or at times when the traffic would not warrant having operators at their switching sections. In the Main office there were order wires from every A position to the four outgoing trunk operators. There was also a trunking multiple at each position on the board which ended in cords and plugs at the trunk operators' positions. At the outgoing trunk positions the trunk lines to the different offices ended in jacks.

Suppose a manual subscriber wanted to call an automatic number, 39,225, which is in the Highland Park office. When he took his receiver off the hook, the operator responded and ascertained the number wanted; she then used the first order

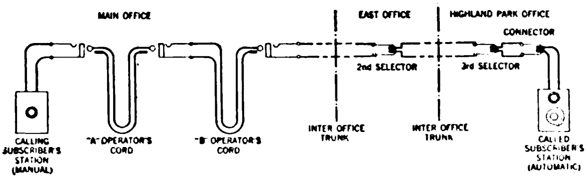


FIG. 9—OUTGOING CONNECTION FROM MAIN OFFICE TO HIGHLAND PARK OFFICE

wire that was not busy and repeated the number to a trunk operator, who assigned the trunk to be used, plugged into a trunk line to the East office and, with a calling device, called **9225**. The first number of the call was omitted because the operator performed the function of the first selector, that of selecting a trunk line to the exchange, when she plugged into the proper jack. Calling 9 operated a second selector in the East office which selected a trunk line to Highland Park, where the call was completed in the regular manner by a third selector and a connector. Suitable supervisory signals were provided for the guidance of the operators. Such a connection is illustrated in Fig. 9.

Of course, the subscribers of the Home company were not acquainted with the steps taken in securing their connections. The manual subscribers knew only that they must make their calls orally, using their telephones as they had been in the habit

[CAMPBELL]

FIG. 11

[CAMPBELL]

FIG. 13

[CAMPBELL]

FIG. 14

[CAMPBELL]

FIG. 15

of doing, and that they secured their numbers. Automatic subscribers understood equally as well that all numbers below 20,000 were called through operators, who were secured by dialing number 1.

The automatic subscribers calling automatic numbers dialed their calls in the way usual with the automatic telephone and without knowledge of the offices or mechanisms concerned. The telephone directory made plain to the users which were manual and which were automatic numbers.

Later Method of making Automatic to Manual Connections. While the arrangement illustrated in Fig. 7 and already described for handling calls from the automatic offices to the manual gave good service, it was slower and more expensive than full automatic service, and therefore, after about two years of operation, by which time the number of automatic lines had increased greatly, it was decided to install equipment which would enable the automatic subscribers to complete connections automatically to all manual subscribers' stations excepting those connected to private-branch exchanges.

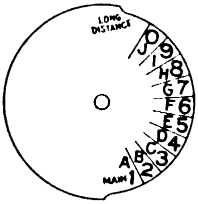


Fig. 10

This was accomplished by ending the trunks incoming from the various automatic offices, in second selector switches installed at Main office. The bank levels 1 to 9 of these second selectors were used to call third selectors, which in turn extended connections to connectors. The banks of these connector switches were multipled to all the manual lines in Main office, excepting the trunks to private-branch exchanges. All Main office numbers from 1000 to 9999 were made into the five digit numbers required for automatic working by prefixing the letter A before them. On the calling devices the letter A was printed beside the figure 1 (see Fig. 10) so that it took the place of the old word Main in the operating instructions.

When this apparatus had been installed at Main office, manual subscribers secured all of their connections as before, but an automatic subscriber who wanted any Main office individual line, simply spelled out on his calling device the desired party's number and secured connection, without an operator's aid, just as if the wanted party had an automatic telephone. An interworking busy test such as that already mentioned as being used between the B board and the automatic switchboard in each of the various automatic offices,

was used between the connector switch banks and the multiple of the manual board in Main office.

To secure connection to a private-branch exchange (P.B.X.) trunk, automatic subscribers were instructed to call 10. The figure " 1 " caused a calling party's first selector to connect his line to an idle trunk to Main office, where a second selector was operated in response to the " O " and extended the connection to an operator, who took the calling party's order and completed the connection, by plugging into the jack of a trunk line to the desired private-branch exchange.

Main Office Abandoned

The next step in the transformation of the system, resulted in the elimination of Main office. This was accomplished by establishing a new central office named Olive in a fire-proof building erected for the purpose five or six blocks from the old Main. Sufficient automatic apparatus, using Keith line switches of the early type then available, mounted on round uprights, (see Fig. 11) was installed in Olive office to accommodate all of the individual subscribers' lines terminating in Main office, and they were gradually switched over to it. A portion of the manual switchboard, thus freed, was moved to Olive Office to handle the P.B.X trunks in so far as calls incoming from them were concerned, while trunking connector switches were installed so that automatic subscribers from that time on made their connections automatically to P.B.X. trunks also.

The company's headquarters were then moved to the Olive office building and the old Main office building was abandoned and sold. The system was then full automatic with the exception that a portion of the old manual board, transferred to Olive, as already mentioned, and a portion of the old B board at each of several of the larger automatic offices were still operated for handling calls from the numerous manual private-branch boards to the automatic subscribers stations. These connections were set up by the methods illustrated in Figs. 8 and 9, *i.e.*, the full manual method shown in Fig. 8 was used when a call was made during the rush hours for a line connected to an outlying automatic office equipped with a B board, while calls during less busy hours or to the smaller automatic offices were made with dials after the manner illustrated in Fig. 9.

In order to permit this method of handling calls outgoing

from the P.B.X's. to be changed to automatic calling it would be necessary to put calling devices on all of the P.B.X. boards and to remodel some or all of their circuits, and the company felt that its organization and resources could be utilized more advantageously in meeting other demands.

Since the system now serves six times as many stations as it did twelve years ago and much of the growth has been paid for out of earnings, it may be imagined easily that all available energy and money have been needed for taking care of enlargements.

General Plant Design. The great extent of the area to be

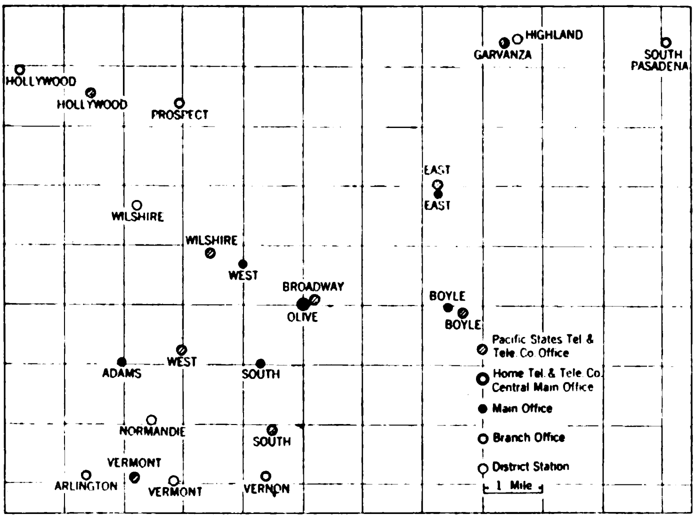


FIG. 12

covered has presented a continuous difficulty. For example, between South Pasadena and a small manual suburban office at Beverly Hills, two offices within the flat-rate unlimited service area, there are twenty-two miles of cable. To maintain a high standard of transmission, a portion of the South Pasadena trunk cable is made up of conductors of No. 16 B. & S. gage and is of special design.

The maintenance of a high standard of transmission throughout the city has been made easier by the comparatively large number of offices used. Increasing the number of offices, shortens the average subscriber's connecting loop. In Fig. 12 are shown the present offices of the Home Telephone & Tele-

graph Company and of the Pacific States Telephone & Telegraph Company. The latter company serves about the same number of subscribers as the Home Company, and, of course, uses the Bell type of manual equipment. It has nine offices, where the Home Company has fifteen. The difference between automatic and manual practise is especially striking in the southern portion of the city, where the Home Company has six offices and the Bell company three. In outlying centers like Hollywood or Highlands, one office is necessary with either type of equipment.

Good, substantial, central-office buildings, especially suited for their purposes, have been erected by the Home Company. The Olive central-office and headquarters building is shown in Fig. 13, Adams office buildings in Fig. 14, and the very simple type of construction used for the smaller outlying offices is typified by the Vernon office building, illustrated in Fig. 15. Buildings of this economical character would not be suitable for manual switchboards with the requisite provisions for the convenience and comfort of the operators.

The character of the outside plant construction is first class throughout the city. Cable is used as much as practicable, and all work is done in a large way with the future in mind.

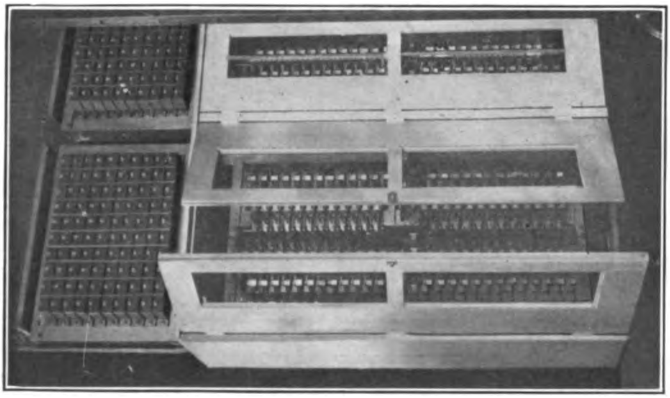
The Present Plant

A skeleton map of the plant as it stands at present is given in Fig. 16. The system includes all of the original Automatic offices and a number of new ones, and serves over 60,000 subscribers' stations.

The number of P.B.X. switchboards is 601, averaging 27 stations each and $3\frac{1}{2}$ trunk lines to Olive office.

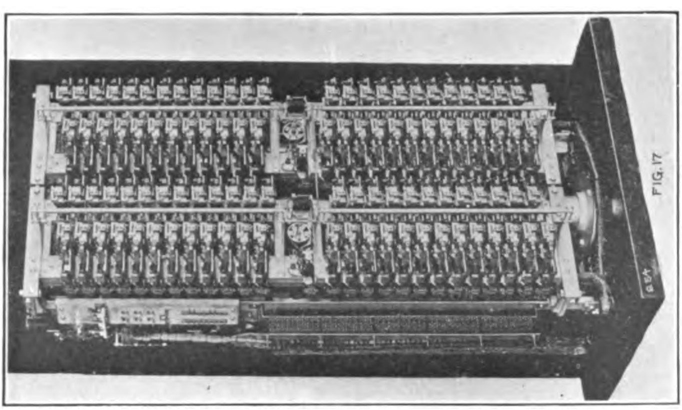
The approximate number of automatic lines and stations connected to each office is shown in Fig. 16 and the numbering scheme is as follows:

Olive Office	A-1000 to A-5999 F-1000 to F-7999	West Office	51,000 to 55,000 556,000 to 557,999
P.B.X. lines	10,000 to 10,999 and 60,000 to 60,999	Wilshire Office	56,100 to 56,799 568,000 to 568,999 569,000 to 569,999 560,000 to 560,999
South Office	21,000 to 25,999 27,000 to 27,999	Hollywood Office	57,000 to 57,800 579,000 to 579,999
Vermont Office	26,000 to 26,899 269,000 to 269,999	Prospect Office	59 000 to 59,899 599,000 to 599,999
Vernon Office	28,000 to 29,999	Adams Office	71,000 to 75,999
East Office	31,000 to 31,999	Normandie	77,000 to 77,999
South Pasadena	35,000 to 35,999	Arlington Office	79,000 to 79,999
Highland Office	38,000 to 39,999		
Boyle Office	41,000 to 41,999		



[CAMPBELL]

FIG. 19



[CAMPBELL]

FIG. 17

It will be noted that in several of the smaller offices six digit numbers are now used, and it follows that some fourth selector switches have been installed in those offices.

The dial number disk used at present is the same as that in Fig. 10, except that the words MAIN and LONG DISTANCE do not appear upon it. To save trunks, a three figure number is now used to call long distance, as mentioned further on.

Types of Equipment. All of the original automatic equipment and that installed at various times since the first installation is still in use although as already mentioned the circuits have been changed to common-battery designs and, recently, changes

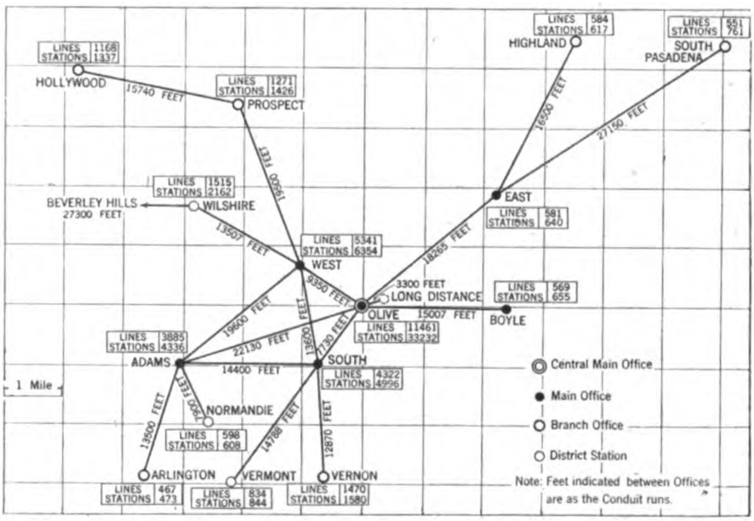


FIG. 16

to Automatic ringing are in progress. Many of the first selectors originally used for line as well as trunking switches have been re-arranged for use as trunking switches only and the lines, which formerly terminated in them, now end in Keith line switches which have been installed more recently. A type of Keith line switch upright similar to that used for many of these changes and extensions is shown in Fig. 17. The use of these uprights in place of the old Strowger switch uprights, shown in Fig. 6, reduces the floor space required per thousand lines of switchboard about 40 per cent.

The unit or "sectional-book-case" designs used in the construction of automatic switchboards have been of great help

in avoiding the sacrifice of any equipment in the many readjustments and enlargements of plant, which have been made necessary by the rapid growth of the city.

Trunk Line Groups. The numbers of trunk lines used between the various offices is given in Fig. 18, which contains many interesting features to which lack of space forbids extended reference.

Traffic. The traffic is quite heavy, averaging per week day 14 to 18 originating calls per automatic station connected to the Olive office, 7 to 9 calls per week day from each station connected to other Automatic offices and 5 to 6 calls from each of the 16,000 stations connected to manual private-branch exchanges.

The average number of originating calls handled per day by each P.B.X. trunk is about 37, which is 50 per cent higher than the average experienced in full manual plants. It is thought that the increased efficiency is partially due to the automatic setting up and disconnecting of calls incoming to the P.B.Xs., which shorten the time each such call occupies a trunk.

The total traffic per week-day sums up to from 500,000 to 600,000 calls, of which about 80,000 are from P.B.X. stations.

The Semi-Automatic or Traffic Distributor Equipment

A step in the direction of changing the P.B.X. trunk lines to full automatic sending was taken in 1914, by removing the last of the B boards from the Automatic offices and installing traffic distributor apparatus, consisting of Keith primary and secondary line switches in Olive office, between the main distributing frame and the A Board used for handling calls received via P.B.X. trunks. In other words, the answering jacks have been removed from this board, and each trunk now terminates in a primary line switch to the banks of which trunks to secondary line switches are multipled. The banks of the secondary line switches are multipled to trunks ending in cords and plugs in the A board.

Therefore, when an operator at a P.B.X. inserts one of her calling plugs into a trunk-jack, a primary and a secondary line switch at Olive office instantly switch that trunk into connection with an idle cord circuit before an idle A operator. If the call is for an Olive office subscriber or for another P.B.X., this A operator completes the connection by plugging into the multiple in the usual way, but if it is for a subscriber in any

Trunks from / Trunks to	A. Olive	P. Olive	West	South	Adams	Wilshire	Vernon	Prospect	Hollywood	Vermont	Boyle	East	Highland	Normandie	So. Pasa	Arlington	Semi-Auto.	Long Distance	Total
Olive			100	80	59						20	32						20	311
West	120	80		60	40	106		67	53		9	14							537
South	116	74	70		60		77			58	8	10							473
Adams	60	49	50	46							5	8		52		25			295
Wilshire			142																142
Vernon	35	25	20	36	10					6	5	6							143
Prospect	20	20	19	11	8	8			11		2	3							102
Hollywood	16	17	40	7	7	6		10			2	5							110
Vermont				80															80
Boyle	18	9	7	8	5							5							52
East	18	10	7	9	6						5		35		30				120
Highland	20	10	7	9	4						3	5							58
Normandie					59														59
So. Pasa	10	10	7	6	5						3	5	7						53
Arlington	8	7	6	7	9						3	3							43
Semi-Auto			100	90	50						7	20						9	254
Long Distance	16	10	15	10	9						5	5					37		107
Total	457	321	590	459	331	120	77	77	64	64	77	121	42	52	30	25	37	29	2939

FIG. 18

of the other offices, she plugs into an automatic trunk and dials the desired number by using a calling device which is now a part of each operator's equipment.

These automatic trunks end in first selectors in the Olive office so that the former plan of having the operators omit the first digit of the called number and manually select a trunk direct to the desired main exchange has been eliminated. Each operator has a set of non-multipled trunks to the first selectors and those switches automatically pick out idle inter-office trunks for her.

The present method has increased the efficiency of the trunks and the accuracy of the dialing, while, at the same time, it has simplified the work of the operators, because they no longer have to mentally divide a number into two sections nor do they have to make a busy test on a trunk before using it.

On account of certain engineering problems, calls to the outlying offices are at the present time sent over special sets of trunks as indicated in Fig. 18; but it is planned to make changes, which will enable all such calls to be sent over the regular automatic trunks, and thus to considerably increase the inter-office trunk efficiency.

The line switches in which the incoming trunks from the P.B.Xs. terminate are arranged in groups of 25 each and each such group has ten outgoing trunks to secondary line switches. The secondary line switches are arranged in groups of twenty, and each group has ten trunks leading to plug ending cord-circuits on the operators' positions.

The line switches are of the latest two-wire type, with self-restoring plungers, and are wired especially for traffic distributor work. The pairs of relays for the line switches are mounted under individual covers on a rack placed above the line switch shelves as shown in Fig. 19.

Thirty operators' positions, are equipped with twenty cord circuits each and are more than sufficient to take care of the peak load from the 600 P.B.Xs. and 100 inter-communicating systems.

The scheme of wiring each of the 10 trunks outgoing from any primary line switch group to a different secondary group, and of wiring each of the trunks outgoing from a secondary line switch group to a different operator's position, is such that a call coming from any P.B.X. trunk is switched to any one of the operators on duty who may be idle at the instant.

The cord circuits are arranged for automatic ringing both on manual and automatic calls and double supervision is supplied. The cord circuits are so designed also that if a calling P.B.X. operator has had a connection established, and wishes to make another call or again secure an A operator for any reason, she can disconnect instantly by releasing the line switches and immediately come in on another cord circuit. This is possible only after a connection has been established, for each call is locked until the A operator receiving it either completes the connection wanted or releases the call by means of a key.

There cannot be more than one uncompleted consecutive call in front of any operator, that is, when any position has received a call it is immediately busied to all other calls, until the operator throws the associated key into the ringing position.

On account of the extremely heavy traffic experienced on the P.B.X. trunks, special provision had to be made for taking care of simultaneous originating calls. It was at first found that occasionally during rush periods two or three calls would appear simultaneously in front of an operator, and it was, therefore, arranged so that the operator would answer only one of them and the others would be switched automatically to idle positions. To ensure instantaneous operators' responses, the line signal lamp on each position is connected to apparatus which transmits a mild buzz to the operators' head-receiver. This buzz is cut off as soon as she throws an answering key.

Provision is made for taking care of extreme peak periods by an arrangement of the primary master switches, which is such that when all the outgoing trunks from any group are busy either because of calls or lack of operators, the master switch will not continue to search for an idle trunk, but the call will be stored in the equipment until a trunk is available. Any operator's position is automatically made busy when she removes her talking-set plug from its jack.

The chief operator's desk is provided with supervisory signals, which tell her at all times how many master switches or groups of trunks are loaded to the limit. A supervisory lamp is provided for every master switch, and by observing these lamps, the chief operator can always tell whether she has enough girls at the switchboard to take care of the load.

The traffic distributor has reduced the number of operators required at the peak load in Olive office from 41 to 30, and has eliminated five B operators' positions formerly used in the

South, West and Adams offices. The engineer of the company estimates that the 30 operators' positions he has equipped will continue to be sufficient even when the business has grown considerably more.

The curves in Fig. 20 show graphically what results have been obtained by the installation of this semi-automatic apparatus. Curve *A* gives the number of un-equated calls handled by each A operator during a peg count taken in September 1914, a month or two before the new equipment was put into service. Curve *C* shows the average number of calls dialed by B operators from the three dialing positions at Olive office to the smaller outlying offices, at the time of the peg count mentioned above.

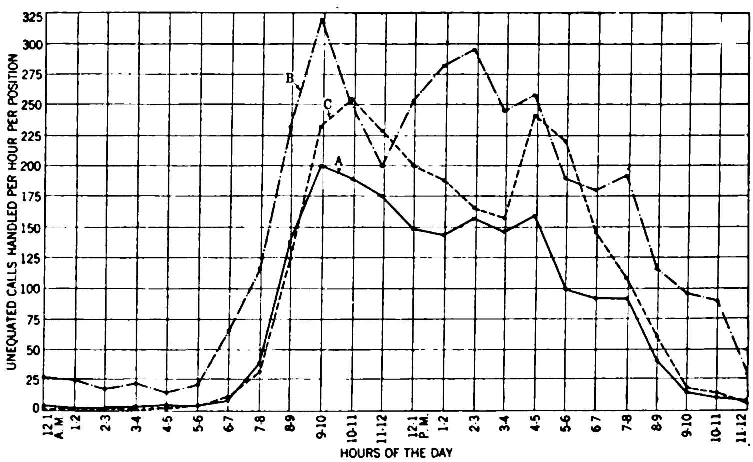


FIG. 20

Curve *B* shows the results in June 1915, with the traffic distributor in operation and the A operators dialing the calls (about 30 per cent of the total) to outlying offices. It is interesting to note that, in spite of the work of dialing, the average operator completes over 50 per cent more connections than she formerly did at the hour of peak load. Both before and after semi-automatic operation individual operators have been required frequently to exceed the average peak load. This excess sometimes ran as high as 50 per cent with the former arrangement, but now rarely exceeds 25 per cent. Neither September nor June are months of as heavy traffic as the winter months, but they represent average conditions fairly well.

The Home company's engineer had all the cord-circuit relays assembled and wired in sets with one base for each cord circuit, so that each cord-circuit equipment looks like an Automatic switchboard repeater, is provided with a jack and is mounted on a regular repeater shelf. The cabling is so arranged that when the Company is ready to change the method of handling the P.B.X. trunks from semi- to full automatic, it will simply mean removing the present cord-circuits from their jacks and replacing them with repeaters designed to transmit impulses direct to first selector switches.

All calls from any automatic telephones to the P.B.Xs. are handled automatically through rotary connectors, just as before the traffic distributer was installed. As already explained, all the P.B.X. trunks are multipled to the banks of these connectors, so that it is impossible for connectors to stop on trunks which are in use either by a P.B.X. for outgoing calls therefrom or by a traffic distributer operator on calls to P.B.Xs.

These connector switches are of special design, for the circuit of each is such that if an automatic subscriber calls a P.B.X. and, when through talking, hangs up his receiver before the attendant at the P.B.X. removes her answering plug from the trunk jack, his connection will not all be released, but, contrary to the usual practise, the connector switch will remain connected to the trunk until the attendant at the P.B.X. removes the plug from the trunk jack. If it were not for this provision, the line switch associated with the trunk would operate, because of the plug being in the jack at the P.B.X. after the connector switch released, just as if the P.B.X. operator were initiating a call. The result would be that a traffic distributor operator would receive a false signal.

To take care of the extremely heavy traffic, 44 connectors are provided for completing calls to each group of 100 P.B.X. unks.

Special Service Facilities

Calls for Time. The Home Company receives thousands of inquiries daily for the time-of-day.

The call-number for such service is F-91. This call switches each inquirer to an idle trunk which leads to the Home Company's own P.B.X. board, at which all such inquiries are answered by the operator on duty.

Since these particular trunks are used for no other purpose, the operator answers a signal on any of them by throwing a

key and stating the hour and minute, without asking the caller what he wants. If several calls come in within a short period of time, thus occupying several trunks at once, she can speak to all of the inquirers at once.

The P.B.X. operator had some spare time, so that she very readily handles this service at no inconvenience or additional cost to the company.

Calls for Information. A party wanting connection to an information operator calls the number F-93, and by means of first, second and third selector switches is trunked to the information board which is located in Olive office.

All of the four to six thousand information calls made daily are handled on an eight-position switchboard and one call distributer position. The incoming information trunks terminate on the distributer position. There is an operator on this position during the busy hours of the day, and her work is to manually route the incoming information calls to idle information clerks.

There are before her eight small groups of jacks connected to trunks to the eight different clerks' positions, and, as the incoming information trunks end in plugs and cords, it is a comparatively easy matter for the distributing operator to plug the calls through as they come in, so that no clerk will have more than one unanswered call in front of her. This ensures practically instantaneous responses. At peak periods, when more than eight information calls may come in at once, the distributer operator herself answers the overflow calls by saying "Information, just a moment, please."

A calling subscriber when so answered, and even if he should have to wait 10 or 15 seconds for his information, is more satisfied than if he had to wait some time without being told he had reached the desired department.

The distributer operator acts also as supervisor over the other information girls. Disconnection supervision is given on the distributer position and on the individual positions. During times of light load all the information trunks are plugged through to a few of the information positions, and the distributer operator and any clerks, who are not required, are dispensed with.

The information desk is four-sided with two clerks' positions on each side and the distributer operator is at a separate desk. Every clerk's postion is provided with an inter-leaved direc-

tory for use in supplying alphabetical information. In the center of this desk is a rotating-turret card-file which affords full numerical and geographical information for the whole plant and to which all clerks' positions have ready access.

Changed-number Service. This service is taken care of at the present time at five different district centers. At each of these centers there is a special test desk used for various purposes, and on this the changed-number trunks are terminated in different groups of jacks corresponding to the various classes of service, such as " take-outs," " moves," " special refers," etc.

Recently the Home company has tried the experiment of connecting the switchboard terminals of " take-outs," *i.e.* subscribers whose telephones have been taken out, to a pair of busbars supplied with current which will produce a peculiar tone in the receiver of any party who may attempt to call such a line and who consequently will be automatically switched into connection with these busbars.

It has been found that subscribers very quickly learn the meaning of such a tone, and in addition to the saving of attendant's hire, there is an advantage to the subscriber in that he will hear this tone in less time than if he had to wait for a clerk to respond.

At one time, all the " dead-level " calls, *i.e.* calls for numbers which have never been used, were answered by attendants, but it was found later to be much more satisfactory to supply this special tone on such connections, and that a subscriber calling an unused number either accidently or otherwise, would almost immediately, upon hearing the tone, hang up and call again. This latter scheme was adopted only after an extended series of tests had been made to determine the reasons for subscribers making dead-level calls. This showed that in very nearly all of such cases, the subscriber had transposed his figures or in some other way confused the called number, and that when informed by the attendant that he had made a mistake, he rarely repeated his error.

On each changed-number position there appears also a multiple of all the outgoing trunks from the office, and the attendant makes periodical tests on every inter-office trunk for impulse and conversation transmission efficiency. In several offices the same girls do general record work also, and answer the calls incoming to the office from company employees.

This changed-number service is handled at five centers instead of one, because it is possible to connect to one trunk only

a limited number of the lines, the calls for which require such service; and on account of the transient nature of a considerable portion of the population of Los Angeles, especially during the tourist season, it would be necessary to use an excessive number of valuable inter-office cable pairs for the changed-number service if it were concentrated at one point.

Complaint Service. The Complaint service call number is "O." Complaints also are received at five district centers. A special feature in Los Angeles is the method for handling the so-called "double-number" complaints. Such complaints are peculiar to automatic plants, and in most cases are such calls as would be satisfied in a manual plant by the operator saying, "They don't answer" or "I am ringing them;" or cases where a supervisor would be summoned to verify busy reports, etc.

In Los Angeles, when a subscriber reports that he cannot get a wanted number, the complaint clerk immediately calls the number desired on an outgoing trunk of her own. If she secures a response from the called party, she then directly switches the complaining party into connection with the called party via the trunk used by her. It has been found that in about 66 per cent of the cases, the complaint clerk is able to get the wanted party.

The complaint clerk is enabled also to cut in on any busy line to determine if it is "busy" because it is actually in use or because the wanted party has left his earphone off its switch-hook. She has means also for testing on any "no-response" call to determine if the bell of the called station is actually being rung or not.

At one time it was the general practise to have an experienced automatic switchboard attendant or tester respond to each of these complaints by asking the calling subscriber to dial the desired number under the supervision of the tester. This was for the purpose of detecting any possible disorder which might have caused the complaint, but inasmuch as the records showed that two-thirds of all such re-calls secured a response from the wanted party, and nearly all of the remainder failed because of legitimate conditions, such as absent subscribers, delayed responses or actually busy lines, it was concluded that this was a very inefficient method for the company, and resulted in much loss of time by calling parties. The present method was therefore adopted.

It was at first suggested that the subscribers might be inclined

to abuse the new method of handling such complaints; that is, that some might be inclined to call a complaint clerk and have her dial all of their numbers for them, but during eighteen months of close observation with the new method in use the "double-number" complaints have not exceeded the original number of 1 per 300 calls, or 1 per station per month. It is, of course, only logical that the fear of abuses should have been ungrounded, because telephone users almost invariably prefer to make their own connections.

Testing Lines and Subscribers Stations. All of the outside plant testing and all dispatching of repair men is done at five district centers. At the one time, each of the fifteen individual offices handled all such work for its own district, but by combining the small districts into larger ones, it was found that the repairmen could be worked at much higher efficiency and that troubles were removed more quickly.

Test-connector switches are installed in all the offices, so that by using his dial the wire-chief or line-tester, at each district center, can make immediate connection to any office and to any line therein that he may have occasion to test.

This centralization of outside plant testing is of comparatively recent development and is thought to be especially practicable in automatic systems. It has been planned to combine some day the present five groups into two or possibly one. That has already been done in the routing and dispatching of service-tap crews, all such work being very satisfactorily handled from one desk in the Olive office.

Method of Setting up Long-Distance Calls. The long-distance lines, to which the Home Telephone and Telegraph Company connects, are owned and operated by the United States Long Distance Telephone & Telegraph Company and serve the commercial district about Los Angeles. They connect in the south with the automatic system at San Diego, run north 200 miles miles to Santa Maria and east to San Bernardino and Red Lands.

Los Angeles subscribers now secure Long-Distance by calling a three figure number, F-95. The first figure of this number gives a calling party an idle trunk to Olive office where the second digit actuates a second selector which picks out an idle trunk to a third selector. This third selector responds to the figure 5, by extending the connection to an idle cord circuit on the position of a recording operator, who takes the patron's order in the way that is common practise everywhere and tells

him that he will be called when the wanted party has been secured.

The only other feature peculiar to automatic practise in handling such a connection is the work done by the line operator in calling the automatic subscriber when the party wanted by him is on the line. All calls from line operators for subscribers in the Olive office are completed by a switching or special B operator in Olive office, who has access to the full multiple of all lines which is used by the operators who handle the P.B.X. trunks. Calls for all other offices are completed by the long-distance operators themselves by means of dials. Each line operator has access to a certain number of outgoing trunks to first selector switches which are situated in the long distance office, and from the banks of these first selectors, trunks are run to the various main offices throughout the city, where they terminate in second selectors.

Long-distance Automatic Calling. Not only do the Los Angeles automatic switches establish about half a million local connections daily, but practically all long-distance calls originating within fifty miles of the city and completed through the Home company's plant are set up by these same switches in response to calling-devices which are installed upon the various long-distance boards in the surrounding territory, and manipulated by the operators presiding over them. In fact, one exchange one hundred miles from Los Angeles dials its calls to subscribers in that city.

This method of setting up and taking down long-distance connections speeds up the service very decidedly and thereby increases both the patrons' satisfaction and the efficiency and earning power of the long-distance lines. One does not realize how very important speed is in a territory served like this by competing long-distance lines, until he learns that it is fairly common practise for a busy patron to order up a desired connection over both lines, to talk over the one which is ready first and to cancel the order given to the slower competitor.

Flexibility of the System. The various kinds of service mentioned in the foregoing pages, and others such as fire calls, police calls, etc. to which reference might have been made, show how flexible is automatic switching equipment and how well adapted to fulfill the requirements of modern telephone service; otherwise it would not have been possible to gradually build up, in the face of the keenest competition, the great successful system serving the people of Los Angeles.

Proper Standards Ensure Good Service. When one not thoroughly

initiated into the mysteries of Automatic telephony is informed that for an average automatic connection in a system like that in Los Angeles, the selector and connector switches perform fifty separate and distinct operations, making a total of over twenty-one million per day for the system, and that if the mechanisms fail in one of these operations, some patron fails to secure the party he calls, the novice wonders that any individual or organization ever had the temerity to attempt to supply telephone service automatically. In fact, he is inclined to accept without question the statement, of an old, dyed-in-the-wool manual telephone engineer, who upon first hearing of an automatic switchboard, exclaimed, "God never intended that telephone service should be given in that way." But as one becomes somewhat better acquainted with the apparatus he begins to understand that the selector and connector switches are all alike in most of their mechanical features and are each constructed and adjusted to operate beyond certain limits of line resistance, capacity, inductance and leakage, which are entirely feasible and practicable. These limits are no narrower in the automatic system than they are in manual systems, and, in truth, the mechanisms readily operate beyond the limits which are necessary to keep the transmission of conversation up to a reasonably good standard. Therefore, although every connector switch in the Los Angeles system must be ready to respond at any time to impulses sent from the calling device of any one of the 45,000 automatic telephones, scattered all over an area of about 200 square miles, no serious difficulty and no element of chance is encountered. Nor is it necessary or possible to adjust each switch to the various lines. On the contrary, the switches are not adjusted to the lines at all, but to certain standard, artificial lines whose characteristics are more severe than those of any of the real lines in the entire system. Thus by the use of a few easily attained standards, an operating problem, which appears at first glance to be very complex and mysterious, becomes so simple that when attacked by the efficient, well supervised organization of the Home Telephone & Telegraph Company the result is unexcelled telephone service—a result much appreciated in the commercial and social life of the city of Los Angeles.

I wish hereby to express publicly my indebtedness to Mr. Leo Keller, chief engineer of the Home company for his valuable assistance in supplying data for this paper.

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CONDITIONS AFFECTING THE SUCCESS OF MAIN LINE ELECTRIFICATION

BY W. S. MURRAY

ABSTRACT OF PAPER

In this paper are laid down the conditions affecting the success, for both the public and the railroad, of a main line electrification project, as they have developed in the author's experience with the New Haven 11,000-volt, 25-cycle, single-phase, overhead contact system. Reliability of service and comfort and cleanliness in operation constitute success from the point of view of the public, while the railroad requires, in addition, economic success. Success is dependent, apart from the engineering, construction, and operating features, entirely upon the *density of traffic*.

A commercially successful electrification is one which cuts the operating expenses of steam-operated territory it has replaced to a figure such that the savings effected are sufficient to justify the investment. The savings in operating expenses made by electrification are, in the order of their importance: saving in fuel; saving in motive-power maintenance and repairs; saving in train-miles.

As specimens of the reliable data being obtained from the operation of the New Haven system, statistics from a recent monthly operating report are presented in tables as follows:

1. The amount, distribution and cost of electric power generated at Cos Cob station.
2. Statistics and operating costs of electric passenger service.
3. Statistics and operating costs of electric freight service.
4. Statistics covering line and equipment failures.

Tables are also presented showing construction costs for catenary construction of different types, including anchor and sectionalizing bridges.

BEFORE touching upon the conditions affecting the success of main line electrification, perhaps it would be best to address ourselves to the question as to what constitutes success. A successful electrification may be considered as such from several viewpoints, and this leads to the necessity of a clear understanding with regard to projected results, both on the part of the railroad and the public.

A successful electrification means, of course, successful transportation by electric motive power. Classifying success into its broadest terms, an electrification may be:

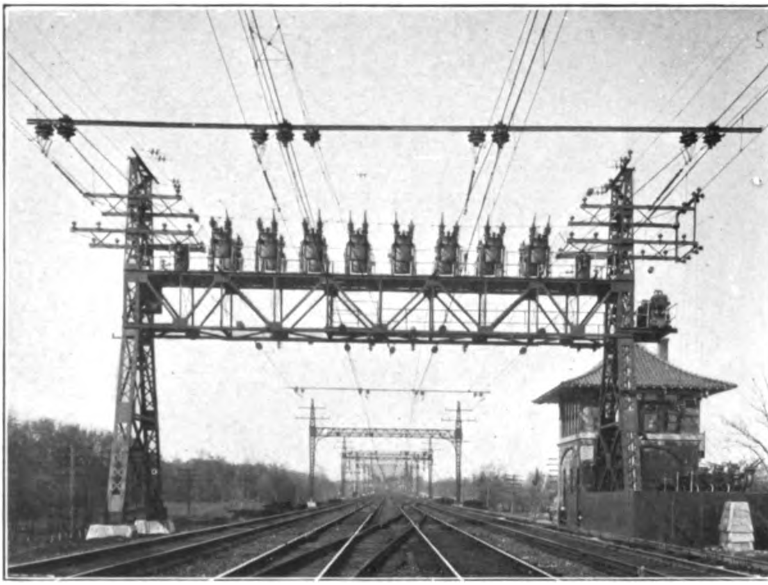
1. A success for the public.
2. A success for the railroad.
3. A success for both the public and the railroad.

Naturally the greatest objective is the attainment of No. 3 of the above classification.

The railroad is vitally interested in the pronouncement by the people as to whether its electrification is successful or not, and, while the viewpoint of the railroad is identical with that of the people throughout their range of vision, looking at it, however, from the purely railroad side, a successful electrification, besides this, must answer the dictates of good business, which in turn are governed by the rules of economic consideration.

In latter times the tremendously decreased gross earnings and a complementary increase in operating expenses have so greatly reduced the net incomes of the railroads that the public have awakened to the fact that they are staggering under a financial load which, if not modified or alleviated in some way, will shortly make receivership the rule rather than the exception.

A few years ago a movement was started by the public to require the railroads to electrify, this being directed towards roads of large size with their attendant city yards and terminals. There were two principal and logical factors against the justice of this demand, the first being that at that time there was very little statistical information as to form, application, and economic result of electrification; and, second, due to the extremely grave financial situation as above described, it was patent that the railroads could not possibly carry the increased financial obligations that such a demand necessitated. The public were thus brought face to face with the undeniable conclusion that they were demanding something impossible, and so there has been a pause on their part, which has indeed been gratefully received by the railroads of this country. Let it be said that this very pause will later shed its dividends over many, for during this time the few railroads that had committed themselves to electrification have had an opportunity to study it in all of its important details and ramifications, and later, after an adjustment has been made whereby the solvency of the railroads of this country is guaranteed by a proper relation between transportation rates and operating expenses necessary to the safe conduct of their business, with enough left over to provide a reasonable return on a fair valuation of the property in use, then, and only then, will the railroad companies be able to do what today they cannot, namely, attract new capital required for electrification; and so, while a reference to this matter may be slightly off the subject of this paper, yet I cannot but take this



[MURRAY]

FIG. 1—FOUR-TRACK TANGENT COMPOUND CATENARY CONSTRUCTION
Showing anchor bridge in the immediate foreground, with sectionalizing switches installed thereon. Signal tower is seen at the right of the tracks, and from this tower sectionalizing switches are controlled. Note also crossover under anchor bridge, with its overhead contact wire.

[MURRAY]

FIG. 2—SIX-TRACK TANGENT COMPOUND CATENARY CONSTRUCTION
Showing electric freight locomotive and train. Freight trains are operated between Harlem River and New Haven, the normal maximum tonnage of which may be, with double locomotive and multiple-unit control, up to 3150 tons. The introduction of freight hauled by electricity has permitted the division to increase the steam tonnage rating twice, reduce time by 33 per cent and train crew expenses to one-half.

opportunity to say in the abstract that this is indeed an important condition precedent to successful electrification.

The pause has given us a chance to learn many things about electrification. I do not believe that I would be conveying information to many who have studied the subject to say that there are probably one hundred places at this moment where conditions are such as to ensure successful electrification. For example, there is one situation I have in mind where an expenditure of $5,000,000 would yield beyond peradventure a return of 20 per cent—this as measured against the present steam operation of the territory contemplated for electrification; and yet in the same breath it might be said that if the yield could be shown to be 40 per cent instead of 20 per cent the electrification of that territory would be denied, and rightly, too. Why? Because, for roads sufficiently large to consider electrification, a sum of this size is small in comparison to their existing capital investment, and a proper relation must first be established between capital already invested and the return upon it before further charges against capital account are made, no matter how attractive the return on the proposed betterment may be.

Quite a number of trunk line railroads, both in this country and abroad, have been studying electrification. The New York, New Haven and Hartford Railroad has not only been studying it most carefully, but has also had the opportunity of assembling data from the practical experience of operation with a range of application that includes all classes of transportation. Millions of ton-miles in these several services have been actually recorded in the logs of the road's operation. In passenger service alone for the year 1913, 2,182,000 electric passenger locomotive-miles were recorded, which alone would represent approximately 600,000,000 ton-miles. The part of the New Haven system that has been electrified constitutes its most important division, extending from New Haven to New York, and on its main line, yards, sidings, and spurs every class of railroad movement is being daily made by electricity. A brief physical description of this division may be as follows:

Route mileage electrified, 73 miles, of which 61 is of four tracks and 12 of six tracks, thus giving a total main line mileage, measured in single track, of 316. To this may be added 184 miles of yards, sidings, and spurs, thus making a grand total, measured upon a single-track basis, of 500 miles. It is of interest to note that of the yards electrified one includes 35 miles, the other 25 miles.

Electric power is supplied to this extensive mileage from a single station, centrally located, but which, in a short time, will be supplemented by other supplies to be applied at the east and west ends of the electrification zone. There are 100 passenger, freight, and switching electric locomotives, and 69 multiple-unit cars. One main electrical shop has been completed, the capacity of which permits the maintenance and repairs of the above-mentioned electric motive power. Facilities for inspection of electrical equipment are also provided at various points in the electrification zone, the more important points being, of course, at termini.

To date, over $15,000,000 has been expended on this electrical transportation plant as above described. While such a figure represents the cash outlay, they have accrued to its appropriation accounts, during the process of construction, large credits for steam equipment replaced, as, for example, the 150 steam locomotives which have been transferred to other parts of the New Haven system, and the steel bodies of the multiple-unit equipment, which would have been purchased even had not the electrification been undertaken.

Descriptive of the electric movement on the New Haven electrification zone, the following facts with regard to passenger, freight, and switching service may be of interest:

Passenger. At the present time all passenger service west of Stamford, Conn., is electrically operated. For the winter time-table now in effect, excluding Sundays, the schedule calls for 68 trains per day into Grand Central Terminal, two through trains terminating in Harlem River Station and the same number of trains out of the Grand Central Terminal and Harlem River, or a total of 140 trains per day.

The Harlem River Branch service includes 19 trains each way per day, except Sundays, between New Rochelle and Harlem River.

On the New Canaan Branch 16 trains are operated each way between Stamford and New Canaan.

This makes a total week-day schedule of 210 trains per day. Additional trains in and out of Grand Central Terminal are operated on Saturdays, and extra trains are also run on the Harlem River Branch on Sundays.

Of the 70 through trains per day between Grand Central Terminal, or Harlem River, and New Haven, 46 are electrically operated the entire distance, steam locomotives being used between New Haven and Stamford on the remaining 24 trains.

Of the 210 trains per day, 114 are hauled by electric locomotives, multiple-unit equipment being used on the remaining 96 trains.

Forty-eight a-c-d-c. locomotives are used in passenger service. The multiple-unit equipment at the present time comprises four a-c. motor cars, 21 a-c-d-c. motor cars, and 46 trailers.

The average number of electric train-miles per day is about 6600, of which 1400 are made by multiple-unit equipment, the remaining being trains hauled by electric locomotives.

The passenger locomotives make an average of 8200 miles per day, some of the individual locomotive mileages being as high as 450 to 500 miles. Forty-one of the 48 passenger locomotives used in a-c-d-c. service were originally designed to haul trains of 200 tons trailing weight in local service, 250 tons in local express service, and 300 tons for through express service between New York and New Haven. At the present time two of these locomotives are only used on through express trains where the trailing weight exceeds 390 tons, and two locomotives may also be used on heavy local trains.

New flash boilers have recently been installed in these 41 locomotives, of increased capacity, to provide for steam heating of through passenger trains between New York and New Haven. This is accomplished successfully. Through service between New New York and New Haven was inaugurated in June, 1914, and these locomotives easily make their running time in express service.

The remaining seven a-c-d-c. passenger locomotives were originally designed to haul local trains of 350 tons trailing weight or express trains of 800 tons trailing weight at a maximum speed of 45 miles per hour. In actual service these locomotives attain a maximum speed of 55 miles per hour.

The multiple-unit motor cars make an average of 2100 miles per day. The proportion of trailers to motor cars for a-c-d-c. equipment averages two trailer cars to one motor car. On the New Canaan Branch the proportion is one trailer car per motor car, while on the Harlem River Branch about one-half the trains have two trailers per motor car, the remaining trains consisting of a motor car and one trailer.

Of 96 trains operated per day by multiple-unit equipment, 38 are Harlem River Branch locals, 32 are New Canaan Branch locals, and the remaining 26 are either locals or local express trains between New York, New Rochelle, Port Chester, Stamford, and New Haven.

Freight. Thirty-six a-c. locomotives are used in freight service. These are geared locomotives of 1400 h.p. each and designed originally to haul a trailing load of 1500 tons in through service at 35 miles per hour, although they are used at times for heavy passenger service in the a-c. zone during the summer months, when heating of the trains is not required. Some of these a-c. locomotives are used in transfer service between Oak Point and Westchester freight yards on the Harlem River Branch others in way freight and switching service, but the majority are used on through freight trains between Harlem River and Bridgeport or New Haven. Outside of the fast freights, which are usually under 1500 tons trailing weight, most of the freights are hauled by two locomotives, the trailing tonnage averaging from 2500 to 3000 tons, although, as an experiment, tests have been made in using three locomotives with trains of over 200 cars and 4500 tons trailing weight.

About 20 freight trains are hauled daily at the present time by electric locomotives between Harlem River and Bridgeport or New Haven.

Switching. Electric switchers are used in the three main switching yards on the Harlem River Branch, located at Westchester, Oak Point, and Harlem River; likewise at Stamford, Port Chester, New Rochelle, Mt. Vernon and at Van Nest, the latter yard being principally used for storage.

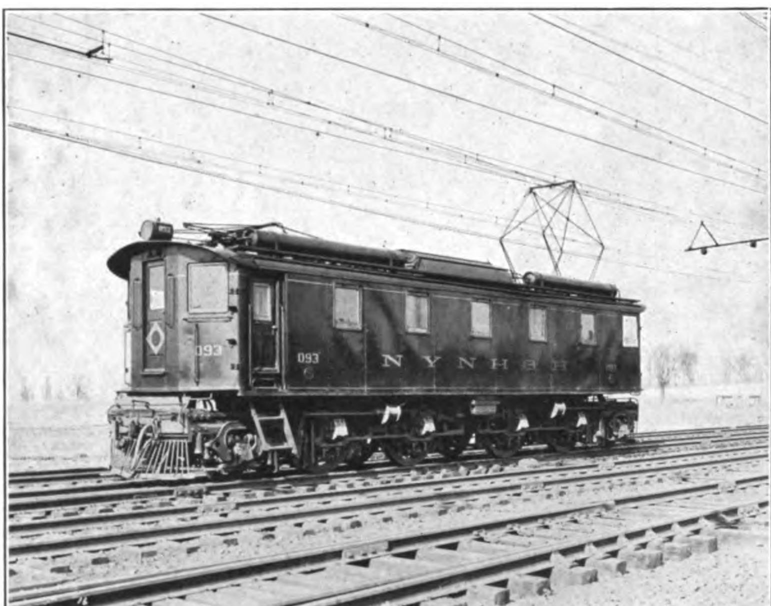
At Oak Point and Harlem River the switchers are used principally for unloading and loading floats and making up trains. One switcher was placed in service in March, 1911, at Stamford, and the remaining 15 have been in operation since September 1912. They have been highly successful in operation, and their reliability is evidenced by the fact that to date there has only been one case of grounded main motor, although the 16 locomotives have made approximately 50,000 miles each. Some of these locomotives have been at times in continuous service 24 hours per day for 30 days, the only attention received being the renewal of blower or compressor motor brushes, or contact shoe of pantograph trolley at such times as change was made of the operating crew.

Four of these electric switchers have been found to do about the same work as six of the steam switchers, which they have displaced, principally on account of the fact that the electric switchers can be used almost continually with no lay-over periods. On account of the simplicity of the equipment on

[MURRAY]

FIG. 3—VIEW IN WESTCHESTER YARD, HARLEM RIVER BRANCH

Showing overhead construction used in electrifying large yards. The cross catenary span in the immediate foreground serves ten tracks. In the case of the Harlem River Yard there are single spans serving eighteen tracks. For equal electrical energy delivered, the cost of this construction is one-third that of the third-rail.



[MURRAY]

FIG. 4—STANDARD STRAIGHT ALTERNATING-CURRENT FREIGHT LOCOMOTIVE

Capable of handling 1500 tons at 35 miles per hour continuously. Weighs 110 tons, 80 per cent of which is on drivers; develops a maximum tractive effort of 40,000 lb., and will maintain a tractive effort of 12,000 lb. continuously. The rated continuous capacity of this electric engine is 1400 h.p. The overhead contact shoe receives a potential of 10,000 volts, which is transformed to 600 volts and in turn is delivered to the terminals of four twin motor equipments in parallel, each motor on the twin combination receiving a maximum normal potential of 300 volts.

these locomotives, used only on alternating current, compared with the more complicated equipment used on the a-c-d-c. locomotives, no trouble has been experienced in breaking in new men, and, as a rule, the engineers need comparatively little preliminary instruction when being transferred from a steam locomotive to an electric switcher.

Mercury Rectifier Car. For some time a motor car has been in service which has been equipped with a Westinghouse-Cooper Hewitt mercury arc rectifier and four 250-h.p. motors. After a period of experimental runs on the Harlem River Branch, this car was placed in commercial service on the New Canaan Branch on September 16, 1914, hauling two trailers, the weight of the trailing load being 76 tons. In this service the motor car has been making an average of 240 miles per day. During the time the car has been in commercial service two delays due to failure of the equipment on the motor car have been recorded—one of three minutes on October 13 due to poor contact of a control interlock finger, and one of sixteen minutes on October 16, due to a broken belt on the circulating water pump.

In 1905, when it became necessary for the New Haven Road not only to actively consider electrification, but promptly decide upon the system to be used, as there was but a scant two years left between that time and the date set by the decree of the New York Court for all New Haven and New York Central trains to operate by power other than steam through the Park Avenue Tunnel, a careful study into the conditions surrounding the New Haven requirements pointed to the necessity of a system different in principle and arrangement from that which had been decided upon and very nearly completed by the New York Central Company—not that the New York Central Company had not made a choice of system which was entirely correct, but because the New Haven conditions were so entirely different from those of the Central. If we regard the New Haven electrification a success, here we must first note conditions that had to be reckoned with to ensure that success.

It was plain to the engineers who had studied these conditions that even in that early day, when the direct-current, 600-volt, third-rail system was at the height of its efficiency and popularity, it would fail by far, when examined upon an economic basis, in the result that would be secured in the use of the high-voltage, single-phase system.

In those days our experience with the a-c. system was *nil*;

a clear vision as to the correctness of its principles, however, more than replaced this lack of experience. To many these were strange arguments to use against a well-tried-out and accepted system, and, while deeply sensible, of a period both difficult and trying to the operators of the road, the burden of this decision had been made light by a willingness on the part of all to take a perspective rather than a foreshortened view of the situation as it has gradually worked its way out of its initiative troubles.

A storm of criticism from all parts of the world assailed our conclusion. As this, however, is ancient history, to say more along these lines would be to say less. This paper, however, might lack a detail not to mention the real reason for which a paper, entitled *The Log of the New Haven Electrification,** presented in 1908 before the American Institute of Electrical Engineers, was written. It seemed to the writer that the thick layer of criticisms shortly after electrical operation was inaugurated, on top of the number that had been received before, required that the discussion be held down to the actual facts in the case, and, knowing that the principles upon which the New Haven electrification was based could not be assailed, and that the log sheet of operation, bad as it was, was merely a reflection of the minor details common to initiative in all new undertakings, it were best to write a paper of the faults that had appeared and the methods used for their correction. This had the desired effect, as the discussion since then has been held within the facts.

It took not a great while to determine upon and eliminate the causes incident to the failures which reflected deleteriously upon the service of the road, and, while the reliability of operation in the electrical zone rose to some three or four times that of the steam operation it replaced, it was not then or even now what it will ultimately be. At this point we touch upon one of the conditions to be satisfied in order that an electrification may be called a success; namely, reliability of service.

The replacement of a steam service which had never been criticised, by an electrical one of increased reliability, naturally brought the pronouncement of success by the public. Indeed, since those first days after the elimination of the troubles which assailed us in our initiative operation there has never been anything other than a favorable comment, both on the part of the public and the technical press. Naturally this was most encouraging to the New Haven engineers.

* TRANS. A. I. E. E., 1908, XXVII, Part II, p. 1613.

About three years following the presentation of *The Log of the New Haven Electrification*, the writer ventured a second paper, entitled *Electrification Analyzed, and its Practical Application to Trunk Line Roads, Inclusive of Freight and Passenger Operation*,* this also being under the auspices of the American Institute of Electrical Engineers, the intention being to present such electrification construction and operating data as he had collected to date, the object of the paper being to show the adaptability of electricity to extensive trunk line movement in all of its branches, covering passenger, freight, and switching on terminal and main line tracks.

In presenting the paper the writer purposely avoided a reference to comparative costs of operation between steam and electricity for two reasons: The first, because of the fact that only a part of the whole division was electrified, and an extremely expensive interchange of steam and electric operation had to be maintained, necessitating expensive duplications and special arrangements which would not have been common to either system had one or the other been used in its entirety upon the whole division. The second has reference to the matter of construction costs, which were exceedingly high in the case of the original electrification between Woodlawn and Stamford—the first undertaken. I am sure it will be of interest to state that in the original electrification the unit cost in 1907 for the four-track overhead system was just double the amount expended on the four tracks recently completed in the section between Stamford and New Haven.

In the discussions before the American Institute of Electrical Engineers and the American Society of Civil Engineers repeated requests were made for a presentation of the construction and operating costs in connection with the New Haven electrification. For the reasons above cited, and because of the fact that the New Haven electrification was decidedly handicapped in being required to build its motive power equipment to operate with either alternating current or direct current, the writer concluded that the time had not arrived where a presentation of these details would serve a useful purpose. Especially was this true in the bitter war that was being waged by parties who were prone to look upon the single-phase system of traction as deterrent to the application of the " more reliable direct-current third-rail system "—then in the flower of its youth, but since gone to seed! (I, of course, have reference to trunk lines.)

*Trans. A. I. E. E., 1911, XXX, Part II, p. 1391.

Here was the problem the engineers of the New Haven Road had placed before them: the consideration of an electrification, the demands upon which would be far beyond any other hitherto constructed or contemplated. The conditions and principles applying to the past and smaller electrifications did not apply to it. Which were to control—the correct principles with the failures always common to initiative, or the wrong principles with a sureness that the service for possibly a number of years would be of a more reliable character? Some of our friends in the technical press have been good enough to say some kind things with regard to the courage of our convictions. It did not take a very great deal of courage to do the right thing, and it cannot be denied that right principles should always govern.

Naturally, ten years of almost undivided attention to electrification work has brought a better knowledge as to how power-houses, lines, locomotives, and shops should be constructed, and I do not believe I overstate when I say that the electrical plant the New Haven now possesses could be reproduced, and with far better operating results, at certainly not more than 60 per cent of its original cost, but, notwithstanding this, when the electric division is on a 100 per cent electrical basis the economic return will be sufficient to justify the electrical expenditure to date.

The recent decision as to choice of system on the part of the Pennsylvania Railroad in favor of single phase for the proposed electrification on the main line between Philadelphia and Paoli, this action being a forecast of the system to be employed in the event of the future financial situation permitting electrification between New York and Washington, was one of no small consequence and pleasure to those who had been toiling to establish a correct application of electrification to trunk line territory.

To those who every day had been in close association with the practical workings of this system initially installed on the New Haven, failures were too closely associated with cause and effect to suggest even disappointment, to say nothing of discouragement, but let me refer to an admirable and fine distinction as evidenced in the decision of Gibbs and Hill, which discounted apparent for real results, and settled that the body of their electrification should be upon a single-phase basis, notwithstanding that the largest terminal upon the same railroad was operated upon a direct-current basis.

I envy, indeed, the result that they should be able to produce for the Pennsylvania Company in the use of straight alternating

[MURRAY]

FIG. 5—MULTIPLE-UNIT TRAIN OPERATING ON SIX-TRACK HARLEM RIVER BRANCH ELECTRIFICATION

This multiple-unit train is also designed for operation on the New York Central direct-current third-rail system. Each motor car has sufficient capacity to haul itself and two trailers.

[MURRAY]

FIG. 6—ELECTRIC SWITCHER NO. 0213, DOING REGULAR SWITCHING SERVICE IN OAK POINT YARD

Four of these engines are capable of doing the work of six steam switchers. They weigh 80 tons, with 100 per cent weight on drivers. They will develop 40,000 lb. tractive effort, and will maintain a tractive effort of 12,000 lb. continuously. Sixteen of these electric engines have recorded over 1,200,000 miles in switching service, and one failure, a burned-out armature, due to a prolonged and excessive load from brakes sticking, is the record of their performance to date.

current upon their lines. Even the record of the New York, Westchester and Boston with its straight alternating equipment whose log sheet reports will show 125,000 miles per car failure, may be surpassed on the Paoli division by this coming Pennsylvania electrification. As I forecast this record that should be made, I review in retrospect some of the experiences that have caused it to be possible. Among the number are generator windings that have torn themselves loose from their housings by action of 11,000-volt short circuits upon their grounded phases; sectionalizing oil switches on the line hurling their cover plates 100 feet in the air, due to these same short circuits; the overhead contact line parting company with itself, due to high-speed pantograph shoes impinging themselves against the hard spots at hanger points; locomotives nosing their way along the tracks with broken quill springs and grounded motors; and so we might go on drawing the picture of our difficulties based upon lack of experience, but the future is the brighter picture. None of the railroads, not one, will have to go through this. It is all behind us, and present operating statistics are now the proof that the high-voltage alternating-current electrification, with its attendant higher efficiency, will be as reliable as the direct-current, if not more so, on account of the simplicity of its control.

Governed by the right principles, we have passed from the days in which we desire to make it work into those in which we must make it pay. Accurate distributions of the costs in all departments of construction in their application to power-house, lines, locomotives, and shops, together with expenses incident to the maintenance and operation of these salient features since the work was first undertaken, have shown a declining curve of unit costs throughout these various details as against the progress of time. Some road had to make the first break into the dark. No. one had any advice to give, as no one had any experience upon which to base it. Some of our critics have been inclined to view the New Haven electrification as a great experiment. They are right—it was; but as an experiment it has given a cleaner and more reliable ride for the public, and in the end will not cost the New Haven road a (economic) penny; but its greatest value in my estimation has not been so much this as the more stable position in which it has placed the other roads to this country to consider electrification, a subject to which they will have to address themselves in the near future.

The larger part of the experimentation is over, and, from the

data assembled, future results, in the application of electricity in heavy trunk line territory, can be predicated on assembled facts, and not predicted from hypothetical analysis. Critics have had it that the so-called "battle of systems" has delayed the electrification of railroads. As an electrical engineer keenly alive to the desirability of interesting railroads in moving their trains by electricity, I am glad if any insistence on my part upon the matter of "system first" has delayed electrification in this country, and argue that every minute of the delay will be a future asset to the railroads.

When we talk about railroads we generally mean trunk lines, and all trunk lines have essentially common and determining characteristics that make the best system of power distribution for one the best for all. Therefore I count it most fortunate that electrification has been delayed. Over the same standard gage, cars of every description can be hauled. Therefore, why not a standard overhead conductor, under which every form of electric motive power can operate?

I recall with interest one of the New York Railroad Club meetings, of which many have been held, typified as their "Electrical Night," at which a committee, previously appointed, reported its recommendations with regard to the application of alternating or direct current to specific situations. Particular stress in this report was laid on the advocacy of direct current for large terminals. This appeared to me as a fallacious conclusion, as the record of my remarks for that evening will doubtless disclose. It was clockwork typified in the movements made in these great New York Central and Pennsylvania direct-current terminal electrifications. A credit indeed was due the splendid corps of engineers who in those early days were responsible for the decision and execution of these works; yet conspicuous for their absence on this committee was that same corps of engineers, for to have subscribed to such an electrification policy would have included their concession that the tail of the dog was to wag his body! The committee made it clear that if the electrification was to be confined to terminal limits, then without question that electrification should be undertaken upon a direct-current basis. Immediately following this recommendation, alternating current was prescribed at best befitting trunk lines. I well recall the hiatus from which my brain reeled as I listened to the speaker divorce the trunk line from its terminal and draw in perpetuity the picture of the one great electrical evil

from which it was desirable to escape; namely, the uncongenial marriage of alternating current to direct current. Fortunately we have learned enough about this matter by experience not to fear the execution of such a policy. As evidence of this fact, one of the simplest proofs is a reference to the wonderful reliability and economy of service to which we are treated in serving the great terminal yards at Oak Point and Harlem River with the straight alternating-current switching locomotive. During the past two years, in which 16 engines of this type have been in operation and in which over 1,000,000 locomotive-miles in commercial switching service have been recorded, there has been, as previously said, just one main motor failure. This however, is touching upon details of which we will speak later, and I have only mentioned it here in support of the argument that all motive power equipment should, if possible, be designed for operation upon one form of current, this being one of the essential conditions precedent to successful electrification.

At this juncture it is of interest to point to the fact that under the single-phase, high-potential contact wire, three types of electric motive power—the single-phase, the three-phase, and the direct-current (through the medium of a rectifier)—can operate; thus each class of equipment is permitted a supply of power unchanging in form.

The principle of cardinal importance to the writer's mind, and one of the conditions affecting the success of main line electrification, may, therefore, be said to be the establishment of a standard system of power distribution, from the contact wires of which shall be delivered power in standard and unchanging form, and, while all electric locomotives or multiple-unit equipment will primarily receive this power in identical form, it may thereafter be modified or transformed to conform to any type of alternating-current or direct-current equipment, which is in turn prescribed by the local conditions. Such a standardization would provide a single high-voltage contact wire running throughout an entire electrification zone upon which are impressed 11,000 volts of 25-cycle, single-phase electricity.

Such a line could have operating beneath it single-phase equipment of the New York, New Haven and Hartford design, three-phase equipment of the Norfolk and Western design, and, finally (through the medium of the rectifier), direct-current equipment of the New York Central design, all of these equipments having entirely dissimilar torque-speed characteristics prescibed as local

conditions demand. I believe that we will all admit that such a standardization offers a wonderful flexibility, but, after all this, flexibility is not the real reason for its acceptance, although we cannot fail to class it as one of the facts that form a part of a correct conclusion. The real reasons are rooted in the field of economy, where the railroad dollar must justify its investment. There is no other distribution and contact system that can touch it in efficiency. Its principles have intertwined themselves with every application of electricity in the variegated field of its usefulness, and in no place is its application more apt than in supplying power for train movement.

Up to this point the writer has possibly levied upon your indulgence in treating his subject upon very general lines, but in so doing there has not been a moment when the specific subject of the paper has not been in mind. The subject itself is such a broad one that in truth it must be said that it has been more difficult to know what not rather than what so say, and what has been said has only been in an effort to show that during his pause we have been schooling ourselves by the analysis of the data secured; sorting it into cost *versus* return; studying comparative results arising under varying conditions; crystallizing out the mistakes that have been made in the past by lack of sufficient experience and information; drawing conclusions that are not guesses on what shall be the future methods to be followed in electrification, and assembling our facts for ready reference and application.

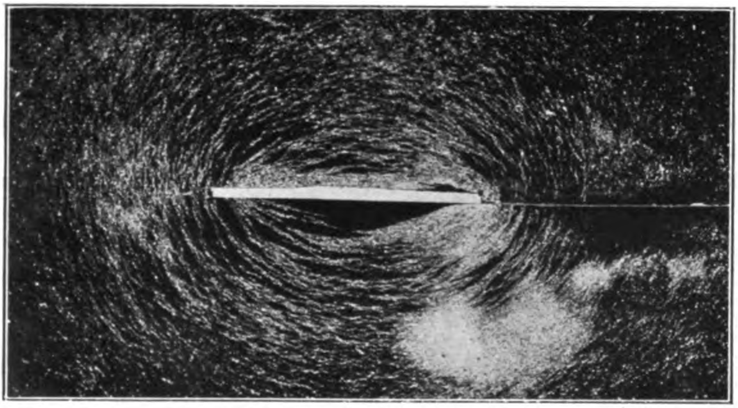
Now, coming to the specific subject of the paper, let me point first to the great underlying condition, apart from the engineering, construction, and operating side, upon which the success of main line electrification, from a combined public and railroad standpoint, is founded: success is entirely dependent upon the *density of traffic*.

A commercially successful electrification may be described as one which, through its agency, cuts the operating expenses of steam-operated territory it has replaced to a figure whereby the savings effected are of an amount sufficient to justify the investment made.

Our experience to date has taught us that electrification points to three principal places where economy of operation can be secured, and in the order of their importance they may be mentioned as follows:

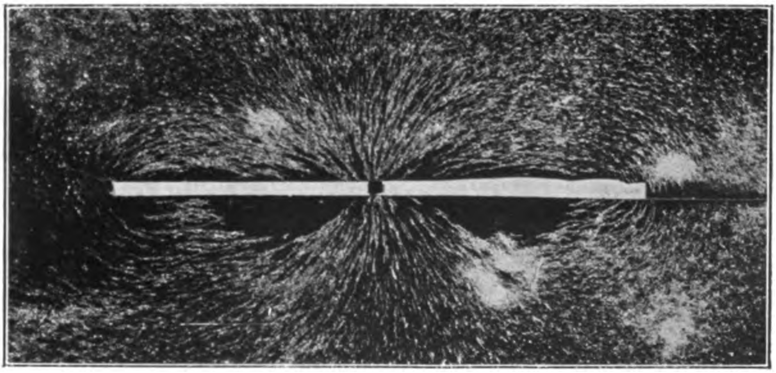
1. Saving in fuel.

MAGNETIC FIELDS SURROUNDING COPPER STRIPS



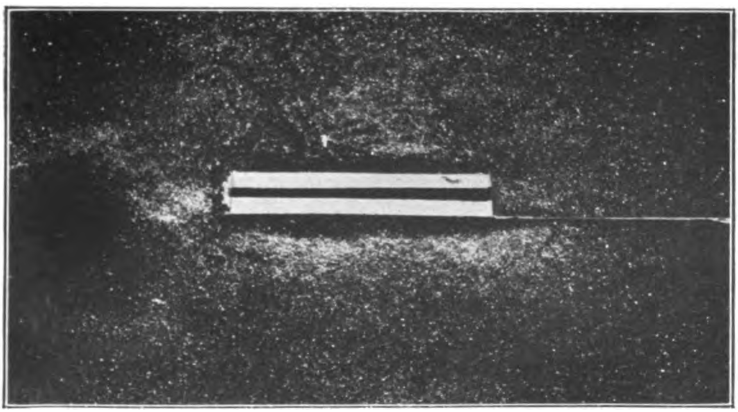
[KENNELLY, LAWS AND PIERCE]

FIG. 11—STRIP CARRYING 107 AMPERES AT 838 ~ A-C.



[KENNELLY, LAWS AND PIERCE]

FIG. 12—OUTGOING AND RETURN STRIPS CARRYING 120 AMPERES AT 858 ~ A-C.



[KENNELLY, LAWS AND PIERCE]

FIG. 13—OUTGOING AND RETURN STRIPS ADJACENT CARRYING 120 AMPERES AT 858 ~ A-C.

2. Saving in motive-power maintenance and repairs.
3. Saving in train-miles.

Assets created by electrification, which may at times be controlling factors, as, for example, the reclamation of city terminal property, after the removal of gas and smoke by the elimination of steam locomotives, are of most important consideration. In cases, however, that do not involve large city terminal electrification, the general credits and debits resulting from electrification work may be said to about offset each other, and thus the value of the returns can be based upon the three items first mentioned. If we know the number of freight and passenger train-miles in a division proposed for electrification, and the cost of each one of the train-miles, today we can say with very little chance of error what the cost of each one of those train-miles in freight and passenger service will be when that division is operated by electricity. If we were to duplicate the steam train movement by an electric train movement a certain economy would be shown, but by reason of the ability to concentrate in single train movements greater tractive efforts and higher speeds, greater individual tonnages can be translated, and thus the third item of economy appears in the reduction of train-miles.

As bearing on the matter of a reduction in train-miles through means of electrification, the three charts (Figs. 7, 8 and 9) applying to studies recently made on the Salt Lake Division of the Denver and Rio Grande Railroad are interesting. In these charts it is of importance to note the great reduction in train movement secured by electrical operation, in combination with the reduction of a section of high grade from 4 per cent to 2 per cent for increases of 20 per cent and 100 per cent in excess of the former tonnage. The example offered is merely illustrative of this application of economy under conditions of electrification.

Experience with the movement of billions of ton-miles in freight, passenger, and switching service by electricity has justified the early predictions that were made in connection with the study of the New Haven electrification; namely, that one pound of coal burned under the boilers of a central electric power station and converted into electrical energy and transmitted to an electric engine will develop twice the drawbar pull at the same speed as a similar pound of coal burned in the firebox of a steam locomotive; and, second, that the maintenance and repairs on electric locomotives of the straight alternating-current type are

on the order of one-half of those required for steam locomotives of equal weight on drivers. It is thus seen that the problem of electrification merely revolves around the question of the destiny of traffic in which the economies aforesaid can be practised, and, therefore, the denser the traffic the greater the requisite motive power for its movement, and hence the greater the saving to be effected. If the schedule of train movement for all roads were the same, then, based upon the number of tons translated, it would be a simple matter to plot a chart which would show two intersecting curves, one of which represented the savings per annum to be effected by the substitution of electricity for steam, the other the summated cost per annum of interest, depreciation, maintenance, insurance and taxes on the electrical plant, inclusive of power-house, lines, locomotives, and shops, necessary to effect these savings, these curves having as common abscissa tons under translation and as ordinates the annual costs respectively represented in the foregoing classes of annual expenditures. The point of intersection of these curves would indicate the density of traffic at which the economic yield of electrification would cover the fixed charges incident to its installation. The curves would also indicate the yield to the railroad that electrification would bring above that of steam operation for traffic densities of greater amount. The analysis, however, is not as simple as this, for, while a number of roads might translate equal tonnages over equal distances, the local conditions might require a wide variation as to schedule; also such physical adjuncts as grade and cost of electric power supply, labor and material clearly make it necessary to give careful consideration to each individual case. The point which I wish to make, however, is that, with knowledge based on experience, operating officials of railroad companies can have an intelligent presentation made to them of the comparative cost relation between steam and electric operation for these several roads. An intimate acquaintance with the ways and methods of the steam railroads of today has taught us how the president, the vice-president, the general manager, the general superintendent, the mechanical superintendent, the division superintendent, the master mechanics, the road foremen of engines, the shop superintendent, and so on down the line to the engineers whose hands are on the levers of either the steam or electric engines, look at operation. Seven years of parallel steam and electric operation on the same division have opened

up a world of perspective to the writer, as he has studied the controlling forces which whirl through the beginnings of this conversion from steam to electricity in the trunk line territory of our American railways.

I would count it a serious omission indeed did I not mention the great and able assistance the present general manager of the New Haven Road, Mr. C. L. Bardo, has given in his study of the operating side of this great electrical problem. It is of him that I think when I touch upon one of the essentially real conditions affecting the success of main line electrification, and that is in the matter of administration. Electricity as an agent of power development is as essentially different from steam as the effects which are produced in the application of heat or cold. The steam locomotive has lived a useful life of eighty years. This is not a prediction that it will not live many more! Even in the clothes of its mechanical ruggedness it is not difficult to conceive of its having once been a pretty delicate machine, deserving of a very great deal of care and attention. The electric locomotive was born of even a more delicate nature, and, while its ruggedness is increasing, it can never possibly be the great mechanical brute that our high-powered steam locomotives may be typified as being today. In the same breath, however, it may be said that the steam locomotive can never reach into the zones of usefulness to which the electric engine can at the present day enter.

It is perfectly possible to keep the maintenance and repairs of the electric locomotive down to one-half of those of steam under the most favorable conditions of steam maintenance, and in many cases below this figure. On the other hand, due to the peculiar nature of the electric engine, which has not as yet been enough appreciated, it will be only by the most rigorous and careful inspection and conformity to rules of operation that this relation can be maintained. Indeed, if electric engines be treated as has been the custom of treating steam locomotives, then their repairs, instead of costing far less, will cost far more than those of the steam engine. The essential difference between the steam and the electric engine is that the former, after it has done all the work it is capable of doing, will lie down, simply stop going, and do this at no cost to its mechanical parts, while an electric engine, like an overwilling horse, if permitted, will work itself to destruction. The commercial life and efficiency of a steam engine may be said to depend on keeping the

heat within its cylinder walls, while the commercial life and efficiency of the electric locomotive are based on how cool you can keep its conductors. In the vernacular of the American youth, some difference! Yet, if you should ask the old steam superintendent operating the new electric division if he agreed to that distinction, the chances are he would say: "Sure, the conductors should never get hot, especially with a passenger." Mr. Bardo has recognized this great difference between steam and electric operation, and in handling the schedule of electric trains he has emphasized the importance of keeping the train loads down to a point within the safe temperatures of the electric motors performing the schedule. The days are passing when with pride the steam operating man points to the electric locomotive as having been able to perform twice the duty for which it was designed, and the next day wonders why the darned old "electric" blew up on half the load. The point to be established, therefore, is that successful electrification requires that there be in the administrative forces minds trained to the necessity of a different viewpoint from that which has come down through these eighty years of steam service. The magnificent organization that has shaped itself throughout these many years and has standardized itself, one might say, in its application to all roads, need not in any way have its fabric torn or changed by the introduction of electricity as a motive power, but there must be established in the administrative forces different minds from those in the past to handle these different things of the future. The future must see well-developed electrical cells in minds of the vice-presidents, general managers, general superintendents, etc., down the line.

An inheritance by the New Haven of the old steam locomotive engineers for the operation of the electric engines is another case where the tail of the dog wags the body. While it is a good argument that these men understand the roadbed and signals better than any one else, this argument fails when engineers without electrical experience or training can bid in the electric runs, depending upon their seniority and record of service. The condition might be alleviated by one set of men, once in remaining in, but there is a constant change, and it is a long time before the steam locomotive engineer divorces himself from the fact that he is not operating a steam locomotive. During his period of learning how to operate the electric engine he does not suffer, the people do not suffer, but the road suffers, and the locomotive

suffers most. Here, therefore, we see the necessity of electrically trained men. The very logic of this stand will ultimately require that these things be so, and one of the successes of which we write in this paper is based upon it being made so.

While all of the main line tracks of the New York division are electrified, there still remains in passenger and freight service, as previously shown, a considerable amount of steam operation, made necessary because the New Haven Road had to avoid capital expenditure for power house and motive power equipment. It can be readily understood that a large reduction in operating expense can be effected when the division is placed upon a 100 per cent electrical basis. On previous occasions when the writer has been dealing with statistics and information made available by his engineering and operating association with the work, he was conscious then, and is now, of the danger, in presenting construction and operating costs, of their possible misinterpretation.

Essentially necessary is a wholesome confidence on the part of railroads undertaking electrification that the result predicted will be attained, and what we are doing on the New Haven today electrically from an operating standpoint could not be better epitomized than by the presentation of one of the last monthly operating reports. The tables that follow comprise the statistics of electrical operation, and give operating information with reference to:

1. The amount, distribution and cost of electric power generated at Cos Cob Station.
2. Statistics and operating costs of electric passenger service.
3. Statistics and operating costs of electric freight service.
4. Statistics covering line and equipment failures.

These records are included in this paper not as an exhibit of something remarkable, but simply to convey to those interested in the electrification of railways the fact that there is daily coming to us a mass of data having reference to the practise of heavy electric transportation, through the agency of which very accurate conclusions may be drawn.

I would ask those who review these statistics with an analytical eye to bear in mind that they are taken from an electrical plant which, from its inception, has been handicapped both from a construction and operating point of view. As before explained, the underlying principle applying to the New Haven electrification required that its motive power equipment be designed to

operate on both alternating-and direct-current power, and that, further, on account of inadequate shop facilities in the past it has been necessary, since securing new shop facilities, to make very heavy repairs throughout the entire electric motive power of the road. I have, therefore, to offer this word of caution in analyzing the statistics that are presented, for it is to be noted that the cost of locomotive repairs is high. For example, referring specifically to the table of operating costs of electric passenger engines, (Table XVIII), it is to be noted that in the month of October the repairs are recorded as 8.56 cents per locomotive-mile, while for November these repairs have increased to 10.61 cents per locomotive-mile. At the first blush this would indicate that the new shop facilities were increasing rather than diminishing maintenance costs. This, however, may be explained by the fact that all of the passenger engines have been undergoing general repairs, and invoices for material were passed in greater amounts for November than for October. Many of the electric locomotives have not received a general overhauling since 1907, and during this time their log sheets of operation show some of the locomotives have made over 350,000 miles.

Showing conclusively, however, what can be done with electrical equipment under the care of a better maintenance, I have taken the first ten engines that have received general repairs and present herewith in Tables I to X, inclusive, segregated monthly costs and mileages made since these engines have passed through the shops.

Notwithstanding these engines are of the alternating-current-direct-current type, it is of interest to note that their records so far show an average cost under five cents per locomotive-mile. It is of particular interest to note that locomotive No. 032, which received its overhaul first, has now operated 93,140 miles at an average cost of 3.6 cents per locomotive-mile.

These maintenance figures for the ten engines give a sharp contrast to those in the general table of passenger engine operating costs (Table XVIII) and emphasize the lack of maintenance to which the electric locomotives were subjected in the early days of their operation. Had conditions permitted our electric passenger engines to be of the straight-alternating-current design, in my opinion their average maintenance would not have exceeded 4 cents per locomotive-mile.

During the past six years of electric operation there have been collected some very valuable data with regard to the amount

of power required to operate trains of variable tonnage in passenger, freight, and switching service. Based upon these data, the power required to operate trains under normal or peak conditions of schedule can be calculated with results practically coinciding with the estimates.

By means of wattmeters installed on all locomotives and motor cars it has been possible to record the differences of power required by trains operating under local and express conditions. The long period over which these statistics were kept and power rate constants thus developed has permitted us to abandon an elaborate tabulation and conslidate the information in the more general statement (Tables XVIII and XIX). Of value to those who are interested to follow more closely these results, Tables XI, XII, and XIII will be of assistance. These tables are compiled from the June, 1914, statistics of electric passenger and freight train operation between Woodlawn and points east to New Haven. At that time the overhead system had only recently been completed to New Haven, and there was but a a small percentage of electric service, both as regards passenger and freight, between Woodlawn and New Haven, and, while the tonnage in both passenger and freight service has been greatly increased since that time, these tables, however, may be taken as giving reliable data in connection with the electric train movements recorded. The watt-hours per ton-mile are secured through meters recording input power to the electric motors. To determine the actual amount of power taken from the contact wire, these figures should be divided by 97 per cent, thus allowing an average loss of 3 per cent for the step-down transformers installed on the electric engines and motive power. As examples of the increments of electric service, since the extension of the electrification to New Haven, while it is to be noted that the total electric passenger ton-miles for June, 1914, were approximately 41,000,000 and that of the freight 9,400,000, the former has now increased to 62,000,000 and the latter to 44,000,000.

Of especial interest to the writer with regard to the tables covering electric passenger operation is the variation in watt-hours per ton-mile for the various express and local services. For example, it is to be noted that the power rate for New Haven express trains eastbound is 31.4 watt-hours per ton-mile, this rate being increased slightly for trains operating to Stamford; the rate rises quite rapidly for trains operating in local service to

Stamford, and continues to rise for local trains operating to Port Chester and New Rochelle respectively. It is, of course, well known that the rate of power supply per ton for express operation is very much lower than that required for local operation, as in the case of the latter the train suffers, under the conditions of braking, the loss of the kinetic energy stored in it under the conditions of acceleration. The increasing watt-hours per ton-mile as shown in the tables are practically proportional to the diminishing distance between train stops. It may also be said that the distance between stops increases progressively east of New York City, and if, for example, suburban territory under consideration for electrification has to be served by train schedule with distances between stations approximately the same as those obtaining on the New Haven Road, the " power rate " constants as shown in these tables will be found to be sufficiently accurate in the study of power necessary to train movement.

In the tabulated statistics covering electric freight operation the point of principal interest is the difference between the rate per ton-mile as indicated in the June tabulation (Table XIII) as against those shown under the general tabulation of freight service (Table XIX), where it is to be noted that the kilowatt-hours for fast and slow freight are, on the average, considerably below 30 watt-hours per ton-mile, this rate being based upon the tonnage of the trailing load. Allowing for the weight of the electric engine, the watt-hours per ton-mile will be reduced to 26, and, as some 200,000,000 ton-miles have been actually recorded by meter registration in freight service, it may be said that 30 watt-hours per ton-mile on level track is a reliable figure, with slight margin to cover electric freight operation in a combination of fast and slow service, *i.e.*, without stops for trains averaging between 1500 and 3000 tons trailing load.

It is of interest at this juncture to point to an interesting experience we have had in connection with the electrical operation of heavy freight trains. It was first thought that when these large train units were placed on the line the power-house would be subjected to very heavy drafts of power under conditions of accelerating them. The reverse, however, was found to be the case, and where, previous to the operation of these trains, the power station output curve showed peaks of a fluctuating character, these heavy trains have served to smooth out the curve of power station output. A reasonable explanation of this would seem to rest in the fact that when a number of the heavy trains

are under translation, and it becomes necessary to accelerate one from rest, the supply of current necessary to this acceleration, while not reducing the line voltage materially, does so, however, to a point which corresponds to a speed of the trains in translation lower than the speed at which they are actually operating, and thus these heavy trains, by their own mass energy, as in the case of a flywheel, automatically release a large amount of power, which becomes available for the accelerating train.

In the foregoing pages I have confined myself to the presentation of operating data, from which I believe very accurate conclusions can be drawn, having regard to the costs incident to electric operation, the only expenses that are materially changed in the conduct of railway transportation being, as previously stated, in the matter of fuel, engine repairs, and train-miles. With definite information developed as to these items, it is not a difficult matter for those experienced in their application to interpolate them into the steam operating accounts in the study of railroads considering electrification. I have thought, therefore, that the broader manner of handling this subject would be not to show concrete cases where the conditions were such as to insure the success of electrification, but rather present the constants of economy that were generally applicable, at least very approximately so, to all railway situations, granting of course, that each individual study would have its qualifying factors which local conditions would control; as, for example, it is quite possible for a complete electrification to turn upon the cost of coal. The greater the cost of coal the stronger is the argument for electrification, from the fuel aspect. For example, if two railroads, one burning \$2.50 coal and the other burning \$5 coal, should electrify, and in each case reduce their coal consumption by 100,000 tons per year, they would respectively save \$250,000 and \$500,000 per annum. In the case of the railroad burning the \$2.50 coal this saving would, at 5 per cent, represent capitalized values amounting to \$5,000,000, while in the case of the railroad burning the \$5 coal the capitalized values would be \$10,000,000. In both cases the capitalized values should be credited against the construction account for electrification.

Savings to be effected in engine repairs are likewise subject to local conditions, for, while it may be said that steam locomotives repairs, upon an average, may be placed at 10 cents per locomotive-mile, on the other hand there may be situations where the railroad has, for example, to use water of severe scaling characteristics and thus run up the cost of repairs excessively.

In the matter of train-miles the savings to be effected are dependent upon local conditions, but it can be stated as a general conclusion, based on a very considerable experience, that:

1. Electric engines on the order of 100 tons on drivers should be maintained at a rate not exceeding 5 cents per locomotive-mile.
2. The coal bill for transportation is cut to at least one-half.

Having determined for any situation what savings can be effected by the substitution of electricity for steam, then, as previously stated, the commercial justification of a change to the new motive power is entirely based upon whether these savings will cover the interest, insurance, depreciation, and taxes on the electrical investment necessary.

In past papers I have refrained from presenting construction costs to show what investment is necessary to operate trunk line territory by electricity, and I believe that this policy will be accepted as having been justified when I state that an analysis of the distribution account of our latest line construction (between Stamford and New Haven) shows its unit costs (four-track) to have been one-half those incurred in the original work, and, while further economics will, of course, follow, I feel that the curve of decreasing electrical investment for electrification has flattened at least enough to present Table XIV, XV and XVI, indicating the costs incident to six-track, four-track, two-track, compound and single catenary, for curves and tangent construction, as a guide to what can be done. To those considering these figures I would offer a word of suggestion that the overhead system of the New Haven Road was designed to coordinate with a road bed which is the throat of the entire eastern New England traffic. Very high safety factors have been included in it, both as regards wire and steel, and it has been many times, particularly during the last season, subjected to high wind velocities, the effects of which have been augmented to ice formation, increasing its projected area.

A general factor of safety of three is prevalent throughout the whole construction, whether on the 200-ft. river transmission towers with 800-ft. spans or on the regular catenary construction, in each instance based on ice coatings of ½ inch all around with wind velocity of 60 miles an hour. I might add, also, that we have been fortunate enough not to have lost a wire due to the above causes throughout the history of the electrification.

Briefly referring to the tables of construction costs, it is to be

noted that the supporting steel bridges have a normal spacing of 300-ft., the trusses of which are designed to withstand the breakage of any of the main supporting messenger wires, and permit also the support at any point of four signals of 2000 lb. in weight each.

As local conditions make different requirements for sectionalization, construction costs are given for continuous catenary construction for tangent and curved track, and, to facilitate the introduction of sectionalizing costs, individual figures for anchor bridge and control sectionalization are given under tables showing costs varying for the different number of tracks under consideration.

Electrification, like everything else, under effects of standardization gets down to a pound or foot basis; the costs tabulated for the different types of construction sectionalization and control may be combined to determine total estimates on work conforming to the requirements of the local conditions.

With regard to electric motive power equipment, papers that have preceded this one have discussed in detail physical dimension, weight, and operating characteristics of electric passenger, freight and switching engines and multiple-unit motor cars. The motive power feature of electrification, like its other parts, has virtually reached the pound stage. Electric locomotives of approximately 100 tons will under present conditions of cost of labor and material, vary between 18 cents and 20 cents per pound. This figure is practically irrespective of speed-torque characteristics, a high-speed passenger locomotive and a low-speed switcher not varying greatly in cost upon a pound basis. Multiple-unit cars, now usually built of steel, do not vary greatly from the above figures, but, if anything, may be quoted as being slightly higher in cost per pound.

The determining characteristics of the locomotives to be purchased in an electrification will, of course, entirely depend upon the local conditions which control the maximum and continuous tractive efforts in passenger and freight service, they in turn depending upon the weight of trains and length of grades, capacity of equipment depending likewise on the two foregoing factors and schedule requirements.

The above approximate quotations on engine costs are presented merely to give a general idea of this department of expense in connection with electrification. As a concrete example in application of the above general statements, I would say that a

first-class, high speed, 100-ton, straight alternating-current electric passenger locomotive, capable of handling a 250-ton trailing load in normal large city suburban service, should cost $40,000. A steam locomotive which would do the same work would probably not cost more than $15,000, but the savings effected, due to the greater operating economy of the electric engine, would represent a figure of twice or three times the amount invested in the electric engine. Thus we might say that for every electric engine we purchase we would be justified at least in making a capital investment of $40,000 to cover the cost of electric power-houses and transmission equipment necessary to supply that electric engine with current. By this reasoning we again approach the answer as to the conditions affecting the success of main line electrification in the fact that it is the density of traffic and in the use of a large number of electric engines by which we can save enough money to pay for the capital expenditure necessary to the supply of power to them for the operation of many trains.

Of late many interesting and valuable papers on electrification have been written, wherein the authors have presented comparable data as between steam and electric operation on specific territory under contemplation.

As mentioned in the earlier pages of the paper, there are many places where electrification would bring a betterment both to the public and to the railroad, but the writer has thought the subject would be better served by a general exposition of his operating and construction experience in connection with a heavy trunk line electrification that has been serving the public for the past eight years, and to draw from it the significant facts and factors from which basic conclusions can be drawn to apply elsewhere.

In concluding the paper I would plead for an especially conservative point of view on the part of the public with regard to electrification. While the savings to be effected under certain conditions of electrification may be considerable, on the other hand the construction investment necessary to these savings may be very great. So many roads in this country have either passed or lowered their dividends, the chief example being a part of the great Pennsylvania system, that it is hardly necessary to emphasize the fact that only a healthy condition of finance throughout the country will warrant the consideration of electrification, and again I would say that partial electrification, such as that applying to yards only and not main line, while it might prove of advantage to a public, might at the same time prove to be a serious and unfair burden for the railroad to carry.

The Public Service Commissions are as much the guardians of the railroads as the people they serve, and the many billions in dollars representing the shrinkage in value of railroad securities in the last few years have awakened in the hearts and minds of the public and the commissioners the fact that no further obligations can be imposed upon the railroads, except they be justified from a fair railroad business standpoint, such equity of treatment describing the duty of the commissioners in whose hands rests the justice of any demand. The electrification of great railroad terminals in particular presents conditions in which the maximum cost is combined with the minimum direct return upon the invested capital, and without some reasonable assurance of adequate return it will be more difficult to secure the necessary capital for such improvements.

TABLE I

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 032.

	1913					
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Labor	32.90	83.01	61.59	23.67	20.18	89.17
Material	20.68	38.61	67.96	21.64	34.56	104.86
Total labor and material	53.58	121.62	129.55	45.31	54.74	194.03
Mileage	4,802	5,517	4,695	4,716	4,687	4,592
Cost per mile	0.011	0.022	0.028	0.010	0.012	0.042
Average cost per mile	0.011	0.017	0.020	0.018	0.017	0.021
Total miles to date	4,802	10,319	15,014	19,730	24,418	29,005
	1914					
	Jan.	Feb.	Mar.	April	May	June
Labor	200.97	85.94	36.52	65.42	91.01	70.70
Material	95.79	27.12	29.15	32.57	70.01	90.28
Total labor and material	296.76	113.06	65.67	97.99	161.02	160.98
Mileage	4,392	6,017	5,310	5,270	5,889	5,839
Cost per mile	0.068	0.019	0.012	0.019	0.027	0.028
Average cost per mile	0.027	0.026	0.024	0.024	0.024	0.024
Total miles to date	33,397	39,414	44,724	49,995	55,884	61,723
	1914					
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Labor	212.36	74.45	147.53	219.47	55.25	....
Material	131.49	156.72	173.96	780.92	146.09*	....
Total labor and material	343.85	231.17	321.49	1000.39	90.84*	....
Mileage	6,165	7,401	5,459	5,678	6,714	....
Cost per mile	0.056	0.031	0.058	0.176	0	....
Average cost per mile	0.027	0.027	0.030	0.039	0.036	....
Total miles to date	67,888	75,289	80,748	86,426	93,140	....

NOTE.—Cost in dollars. * Cr.

TABLE II

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 041.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	17.15	72.04	169.91	113.51	105.56	195.78
Material	8.92	78.24	362.15	288.68	32.29*	473.13
Total labor and material	26.07	150.28	532.06	402.19	73.27	668.91
Mileage	2,912	7,974	8,031	5,990	6,096	5,965
Cost per mile	0.009	0.018	0.066	0.067	0.012	0.112
Average cost per mile	0.009	0.016	0.037	0.044	0.038	0.050
Total miles to date	2,912	10,886	18,917	24,907	31,003	36,968

NOTE.—Cost in dollars. * Cr.

TABLE III

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 037.

	1914							
	April	May	June	July	Aug.	Sept.	Oct.	Nov.
Labor	35.93	61.68	72.78	93.79	119.65	107.20	75.63	115.50
Material	4.69	35.94	159.83	102.73	212.87	184.26	209.81*	47.34
Total labor and material	40.62	97.62	232.61	196.52	332.52	291.46	134.18*	162.84
Mileage	538	4,020	5,641	7,643	8,341	7,203	7,217	6,367
Cost per mile	0.075	0.024	0.041	0.026	0.040	0.040	0	0.026
Average cost per mile	0.075	0.030	0.036	0.032	0.034	0.036	0.026	0.026
Total miles to date	538	4,558	10,199	17,842	26,183	33,386	40,603	46,970

NOTE.—Cost in dollars. * Cr.

TABLE IV

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 028.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	2.04	63.12	135.80	119.00	259.41	78.35
Material	17.25	25.15	211.95	221.73	159.11	39.25
Total labor and material	19.29	88.27	347.75	340.73	418.52	117.60
Mileage	2,103	3,902	6,788	5,398	6,526	8,256
Cost per mile	0.009	0.023	0.051	0.063	0.064	0.014
Average cost per mile	0.009	0.018	0.036	0.044	0.049	0.040
Total miles to date	2,103	6,006	12,794	18,192	24,718	32,974

NOTE.—Cost in dollars.

TABLE V

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 020.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	50.54	148.29	129.71	120.20	127.45	76.35
Material	29.84	30.19	64.29*	195.31	55.41	248.09
Total labor and material	80.38	178.48	65.42	315.51	182.86	324.44
Mileage	5,391	7,997	8,175	7,227	6,664	6,348
Cost per mile	0.015	0.022	0.008	0.043	0.027	0.051
Average cost per mile	0.015	0.019	0.015	0.022	0.023	0.027
Total miles to date	5,391	13,388	21,563	28,790	35,454	41,802

NOTE.—Cost in dollars. * Cr.

TABLE VI

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 016.

	1913	1914				
	Dec.	Jan.	Feb.	March	April	May
Labor	23.52	71.03	108.88	78.80	132.74	106.13
Material	52.16	46.61	55.88	29.91	77.26	51.72
Total labor and material	75.68	117.64	164.76	108.71	210.00	157.85
Mileage	3,260	4,820.5	5,300	5,139.5	4,868	4,222
Cost per mile	0.023	0.024	0.031	0.021	0.043	0.037
Average cost per mile	0.023	0.024	0.027	0.025	0.029	0.030
Total miles to date	3,260	8,080.5	13,380.5	18,520	23,388	27,610
	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	155.66	93.52	112.85	129.38	108.75	221.59
Material	179.80	91.61	152.97	21.28	64.64	13.86*
Total labor and material	335.46	185.13	265.82	150.66	173.39	207.73
Mileage	4,347.5	8,282	8,386	5,644	8,096	5,236
Cost per mile	0.077	0.022	0.032	0.027	0.021	0.040
Average cost per mile	0.037	0.033	0.033	0.033	0.031	0.032
Total miles to date	31,957.5	40,239.5	48,625.5	54,269.5	62,365.5	67,601.5

NOTE.—Cost in dollars. * Cr.

TABLE VII

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 01.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	0	96.38	156.60	175.30	133.64	81.76
Material	0	285.76	351.57	312.04	84.85	15.03*
Total labor and material	0	382.14	508.17	487.34	218.49	66.73
Mileage	571	7,183	7,396	6,006	5,812	6,842
Cost per mile	0	0.053	0.069	0.081	0.038	0.010
Average cost per mile	0	0.049	0.059	0.065	0.059	0.049
Total miles to date	571	7,754	15,150	21,156	26,968	33,810

NOTE.—Cost in dollars. * Cr.

TABLE VIII

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 019.

	1914				
	July	August	Sept.	Oct.	Nov.
Labor	22.07	121.75	84.22	145.20	110.45
Material	4.18	406.70	207.84	129.73	317.68
Total labor and material	26.25	528.45	292.06	274.93	428.13
Mileage	2,886	7,894	7,766	6,938	5,056
Cost per mile	0.009	0.067	0.039	0.040	0.084
Average cost per mile	0.009	0.051	0.046	0.044	0.051
Total miles to date	2,886	10,780	18,546	25,484	30,540

NOTE.—Cost in dollars.

TABLE IX

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 05.

	1914						
	May	June	July	Aug.	Sept.	Oct.	Nov.
Labor	29.82	109.64	43 .55	117.45	113.10	235.34	88.80
Material	83.60	71.29	30.86	309.76	148.05	322.91	129.96
Total labor and material	113.42	180.93	74.41	427.21	261.15	558.25	218.76
Mileage	2,268	5,432	7,937	8,566	5,497	6,783	6,578
Cost per mile	0.05	0.033	0.009	0.050	0.047	0.082	0.033
Average cost per mile	0.05	0.038	0.024	0.032	0.036	0.044	0.043
Total miles to date	2,268	7,705	15 ,637	24,203	29,700	36,483	43,061

NOTE.—Cost in dollars.

TABLE X

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 011.

	1914						
	May	June	July	Aug.	Sept.	Oct.	Nov.
Labor	34.55	43.59	145.87	114.21	211.08	74.86	166.71
Material	61.61	18.69	85.08	230.08	316.83	128.33	70.75
Total labor and material	96.16	62.28	230.95	344.29	527.91	203.19	237.46
Mileage	1,017	5,671	6,243	6,837	6,078	8,122	5,690
Cost per mile	0.094	0.011	0.037	0.050	0.087	0.025	0.042
Average cost per mile	0.094	0.023	0.030	0.037	0.049	0.043	0.043
Total miles to date	1,017	6,688	12,931	19,768	25,846	33,968	39,658

NOTE.—Cost in dollars.

TABLE XI.

STATISTICS COVERING ELECTRIC PASSENGER MOVEMENT AND "POWER RATE" CONSTANTS FOR DIFFERENT SERVICES—EASTBOUND.

	New Haven express trains	Stamford express	Stamford local	Port Chester trains	New Rochelle trains	Total
Number of trains	52	901	667	185	2	1,807
Number of locomotives	84	1,407	859	214	2	2,566
Number of cars	497	7,054	3,875	1,000	10	12,436
Tonnage	35,625	566,033	279,904	67,884	619	950,065
Train-miles	3,120	18,921	14,003	2,405	8	38,457
Locomotive-miles	5,048	30,954	18,894	2,889	8	57,793
Car-miles	29,304	148,134	80,263	13,000	40	270,741
Ton-miles	2,108,700	11,886,253	5,832,923	882,492	2,456	20,712,824
Kw-hr. used	66,076	405,835	343,846	58,933	222	874,912
Watt-hr. per ton-mile	31.4	34.2	59.0	66.7	90.2	42.2

Stamford local trains include one train, New Rochelle to Stamford.

TABLE XII.

STATISTICS COVERING ELECTRIC PASSENGER MOVEMENT AND "POWER RATE" CONSTANTS FOR DIFFERENT SERVICES—WESTBOUND.

	New Haven express trains	Stamford express	Stamford local	Port Chester trains	New Rochelle trains	Total
Number of trains	49	958	604	185	0	1,796
Number of locomotives	78	1,502	791	185	......	2,556
Number of cars	434	6,994	3,941	972	......	12,341
Tonnage	31,963	574,569	261,202	62,559	......	930,293
Train-miles	2,940	20,118	12,684	2,405	......	38,147
Locomotive-miles	4,620.5	33,044	17,402	2,497.5	......	57,564
Car-miles	24,855.5	146,870	81,676	12,591	......	265,992.5
Ton-miles	1,899,957	12,065,689	5,441,943	811,539	......	20,219,128
Kw-hr. used	60,900	486,203	346,935	62,734	......	956,772
Watt-hr. per ton-mile	32.0	40.3	63.7	77.3	......	47.4

TABLE XIII.

STATISTICS COVERING ELECTRIC FREIGHT MOVEMENT AND "POWER RATE" CONSTANTS FOR EASTBOUND AND WESTBOUND SERVICE.

	Eastbound	Westbound	Total
Number of trains	109	116	225
Number of locomotives	109	117	226
Number of cars	2,939	2,829	5,768
Tonnage	106,905	86,706	193,611
Train-miles	5,273	5,564	10,837
Locomotive-miles	5,486	5,784	11,270
Car-miles	142,542	135,792	278,334
Ton-miles	5,184,893	4,161,888	9,346,781
Kw-hr. used	170,259	137,048	307,307
Watt-hr. per ton-mile	32.8	33.0	32.9

TABLE XIV.

COST FOR CATENARY CONSTRUCTION

6-track compound catenary	Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft. span	Curve 1°-1′ to 2°-0′ 300-ft. span	Curve 2°-1′ to 3°-0′ 300-ft. span	Curve 3°-1′ to 4°-0′ 260 ft. span with pull-off
Steel	$14,390	$17,810	$19,600	$23,480	$27,500
Concrete	4,920	5,640	6,330	7,600	10,600
Catenary material	16,650	16,650	16,650	16,650	17,910
Catenary labor	2,800	2,900	2,900	2,900	3,220
Total	$38,760	$43,000	$45,480	$50,630	$59,230

4-track compound catenary	Tangent 300-ft. span	Curve 0°-1′ to 1°-15′ 300-ft. span	Curve 1°-16′ to 2°-15′ 300-ft. span	Curve 2°-16′ to 3°-1′ 260-ft. span	Curve 3°-1′ to 4°-45′ 260-ft. span with pull-off pole
Steel	$9,350	$11,530	$13,280	$15,800	$18,850
Concrete	3,110	2,890	4,080	4,700	7,640
Catenary material	11,050	11,050	11,050	11,360	12,060
Catenary labor	1,980	2,080	2,080	2,080	2,390
Total	$25,490	$27,550	$30,490	$33,940	$40,940

2-track compound catenary	Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft. span	Curve 1°-1′ to 2°-30′ 300-ft. span	Curve 2°-31′ to 2°-30′ 260-ft. span	Curve 3°-31′ to 4°-0′ 200-ft. span	Over 4°-1′ curve 200-ft. span with pull-off pole
Steel	$6,900	$7,220	$7,830	$9,030	11,400	$16,160
Concrete	3,580	3,580	4,280	4,910	6,380	10,300
Catenary material	5,580	5,580	5,580	5,680	5,870	6,520
Catenary labor	1,130	1,230	1,230	1,300	1,310	1,410
Total	$17,190	$17,610	$18,920	$20,920	$24,960	$34,450

2-track single catenary	Tangent and curves up to 2°-30′ 300-ft. span	Curve 2°-31′ to 3°-31′ 260-ft. span	Curve 3°-31′ to 4°-30′ 200-ft. span	Curves above 4°-30′ with pull-off pole 200-ft. span
Steel	$6,680	$7,700	10,500	$14,900
Concrete	3,000	3,300	4,600	4,300
Catenary material	3,530	3,600	37,60	9,000
Catenary labor	510	510	525	650
Total	$13,720	$15,110	$19,385	$28,850

TABLE XV.

COST FOR CATENARY CONSTRUCTION.

COST FOR ONE MILE SINGLE TRACK OF A SIX-TRACK ROAD COMPOUND CATENARY.

Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft. span	Curve 1°-1′ to 2°-0′ 300-ft. span	Curve 2°-1′ to 3°-0′ 300-ft. span	Curve 3°-1′ to 4°-0′ 260-ft. span with pull-off pole
$6,460.00	$7,166.60	$7,580.00	$8,438.60	$9,870.00

COST OF ONE MILE SINGLE TRACK OF A FOUR TRACK ROAD COMPOUND CATENARY.

Tangent 300-ft. span	Curve 0°-1′ to 1°-15′ 300-ft. span	Curve 1°-16′ to 2°-15′ 300-ft. span	Curve 2°-16′ to 3°-0′ 260-ft. span	Curve 3°-1′ to 4°-45′ 260-ft. span with pull-off
$6,372.50	$6,887.50	$7,622.50	$8,485.00	$10,235.00

COST OF ONE MILE SINGLE TRACK OF A TWO-TRACK ROAD COMPOUND CATENARY.

Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft. span	Curve 1°-1′ to 2°-30′ 300-ft. span	Curve 2°-31′ to4°-1′ 260-ft. apan	Curve 3°-31′ to 4°-1′ 200-ft. span	Curve over 4°-1′ 200-span with pull-of pole
$8,595	$8,805	$9,460	$10,460	$12,480	$17,225

COST FOR ONE MILE SINGLE TRACK OF A TWO TRACK ROAD SINGLE CATENARY.

Tangent and curves up to 2°-30′, 300-ft. span	Curve 2°-31′ to 3°-30′ 260-ft. span	Curve 3°-31′ to 4°-30′ 200-ft span	Curves above 4°-30′ with pull-off pole.
$6,860	$7,555	$9,692	$14,425

COST FOR AN ANCHOR—AND SECTIONALIZING—BRIDGE.

	Compound catenary			Single catenary 2 track
	6 track	4 track	2 track	
Steel	$3,200	$1,600	$900	$620
Concrete	2,000	1,270	960	700
Floor on upper deck of bridge	200	160	100	100
Control apparatus and connections	8,000	6,300	4,500	4,500
Sectionalizing	600	400	200	200
Total	$14,000	$9,730	$6,660	$6,120

TABLE XVI.
COST FOR CATENARY CONSTRUCTION.

One mile of four-track single catenary	Tangent 300-ft. span	Curve up to 2°-0′ 300-ft. span	Curve 2°-1′ to 3°-0′ 260-ft. span	Curve 3°-1′ to 4°-0′ 200-ft. span	Curve above 4°-1′ 200-ft. span with pull-off
Steel	$8,800.00	$11,830.00	$13,490.00	$17,500.00	$20,500.00
Concrete	2,930.00	3,940.00	4,200.00	5,640.00	8,640.00
Catenary material	7,035.00	7,193.40	7,260.00	7,415.00	8,170.00
Catenary labor	1,237.60	1,311.50	1,320.00	1,339.00	1,540.00
Total	$20.002.60	$24,274.90	$26,270.00	$31,894.00	$38,850.00
One mile of single track of a 4-track road	**Tangent 300-ft. span**	**Curve up to 2°-1′ 300-ft. span**	**Curve 2°-1′ to 3°-0′ 260-ft. span**	**Curve 3°-1′ to 4°-0′ 200-ft. span**	**Curve above 4°-1′ 200-ft. span with pull-off**
Single catenary	$5,000.15	$6,068.74	$6,567.50	$7,973.50	$9,712.50

Anchor and sectionalizing bridge for four-track single catenary.	Steel	$1,200.00
	Concrete	960.00
	Floor on upper deck of bridge	160.00
	Control apparatus and connections	6,300.00
	Sectionalizing	400.00
	Total	$9,020.00

TABLE XVII.

THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD COMPANY. STATISTICS OF ELECTRICAL OPERATION—NEW YORK AND SHORE LINE DIVISIONS. FOR THE MONTH OF NOVEMBER, 1914, COMPARED WITH THE MONTH OF OCTOBER, 1914.

COS COB POWER HOUSE.

	November		October	
	Total	Per kw-hr.	Total	Per kw-hr.
Coal consumed (tons)	12,439.44	2.78 lb.	12,280.84	2.75 lb.
Water consumed (gals)	38,778,000	4.33 gal.	35,835,000*	4.01 gal.*
Cost of coal	34,084.07	0.381 cent	33,526.69	0.375 cent.
Cost of water	1,582.15	0.017	5,015.55*	0.057*
Cost of other supplies	317.20	0.004	655.85	0.007
Maintenance of power plant and machinery	3,655.27	0.041	3,434.87	0.038
Wages and salaries	6,056.62	0.068	6,704.00	0.075
Total cost, maintenance and operation	45,695.31	0.511	49,336.96*	0.552*
Fixed charges (interest, taxes and insurance)	16,106.89	0.180	16,106.89	0.180*
Total cost	61,802.20	0.691	65,443.85*	0.732*
Power Consumption (kw-hr.)				
Passenger service (elec. locos.)	2,894,465		3,072,145	
Passenger service (M.U. Cars)	630,039		499,367	
Freight service	1,508,306		1,494,082	
Switching service	984,255		848,613	
Non-Revenue service	10,340		6,191	
Total used by electric locomotives and motor cars	6,027,405		5,920,398	
Signals	107,465		117,445	
Other company purposes	389,652		399,401	
Line loss	543,235		617,804	
Total used for company purposes	7,067,757		7,055,048	
New York, Westchester & Boston	676,144		636,058	
Other companies	1,205,699		1,255,139	
Total power used	8,949,600		8,946,245	
Maximum daily output	Tuesday, November 24th 343,300 kw-hr.		Friday, October 30th 316,630 kw-hr.	
Maximum swing	30,000 kw. Friday, Nov. 6—7.00 P.M.		29,800 kw. Sunday, Oct. 4—8.27 A.M.	
Maximum daily output	Tuesday, November 3rd 249,800 kw-hr.		Sunday, October 18th 256,155 kw-hr.	
Average daily output	301,902 kw-hr.		288,589 kw-hr.	
Power purchased from N. Y. C.				
Power purchased (kw-hr.)	1,244,021		1,306,017	
Cost of power	$16,097.67		$16,348.47	
Cost per kw-hr. (cents)	1.294		1,252	
Total Power:				
Total power consumed (kw-hr)	10,193,621		10,252,262	
Total cost of power (including fixed charges)	$77,890.87		$81,792.32*	
Cost per kw-hr. (cents) (charges)	0.764		0.789*	

*Revised.

TABLE XVIII. THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD COMPANY

STATISTICS OF ELECTRICAL OPERATION NEW YORK AND SHORE LINE DIVISIONS. MONTH OF NOVEMBER, 1914, COMPARED WITH MONTH OF OCTOBER, 1914.

Passenger Service.

	Express trains				Local trains				Multiple-unit trains			
	Eastbound		Westbound		Eastbound		Westbound		Eastbound		Westbound	
	November	October	November	October	November	October	November	October	November	October	November	October
Train-miles	49,436	50,385	53,768	54,032	29,128	32,941	23,839	28,622	21,569	19,338	22,552	19,363
Locomotive-miles	82,298	85,220	88,898	89,162	41,148	45,008	31,558	39,722	29,937	28,504	32,220	28,857
Car-miles	386,883	404,166	410,574	425,363	157,770	182,564	137,502	172,338	76,544	74,004	79,292	72,793
Ton-miles	23,880,554	24,483,292	24,654,186	25,697,939	7,314,489	8,444,023	6,432,307	7,812,994	5,093,352	4,755,814	5,296,525	4,684,919
Kw-hr. used	1,120,801	1,133,588	1,231,060	1,220,947	643,284	719,423	524,871	651,374	346,385	305,267	341,496	279,137
Locomotive-miles per train mile	1.66	1.69	1.65	1.65	1.41	1.37	1.32	1.39	1.39	1.47	1.43	1.49
Car-miles per train-mile	7.83	8.02	7.64	7.87	5.42	5.54	5.77	6.02	3.55	3.83	3.52	3.76
Kw-hr. per train-mile	22.67	22.50	22.90	22.60	22.09	21.84	22.02	22.76	16.06	15.79	15.14	14.42
Kw-hr. per locomotive-mile	13.62	13.30	13.85	13.70	15.63	15.98	16.63	16.40	10.71	11.57	10.60	9.67
Kw-hr. per car-mile	2.90	2.80	3.00	2.87	4.08	3.94	3.82	3.78	4.53	4.12	4.31	3.83
Kw-hr. per 1000-ton-mile	46.93	46.30	49.93	47.51	87.95	85.20	81.60	83.37	68.01	64.19	64.48	60.22

Operating Costs.

	Locomotive repairs		Power		Locomotive supplies		Engine house expenses		Enginemen		Trainmen		Total	
	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.
Trains hauled by locomotives:														
Cost per train-mile (cents)	17.15	13.80	19.33	19.89*	2.23	1.53	0.57	0.54	8.81	8.37	5.91	9.55	57.60	53.68*
Cost per locomotive-mile (cents.)	10.61	8.56	11.96	12.29*	1.39	0.95	0.38	0.34	5.41	5.20	5.88	5.91	35.63	33.25*
Cost per car-mile (cents)	2.45	1.93	2.76	2.79*	0.32	0.21	0.08	0.08	1.26	1.17	1.36	1.34	8.23	7.52*
Multiple-unit trains:														
Cost per train-mile (cents)	15.27	11.83	11.39	11.42*	0.24	0.16	0.91	0.78	5.17	5.20	8.84	7.53δ	41.82	36.92*
Cost per motor-car mile (cents)	10.51	7.98	7.84	7.70*	0.17	0.11	0.62	0.53	3.56	3.51	6.08	5.08δ	28.78	24.91*
Cost per car-mile (cents)	4.32	3.12	3.22	3.01*	0.07	0.04	0.25	0.21	1.46	1.37	2.52	1.98δ	11.85	9.73*

*Revised

TABLE XIX. NEW YORK NEW HAVEN AND HARTFORD RAILROAD COMPANY.

STATISTICS OF ELECTRICAL OPERATION, NEW YORK AND SHORE LINE DIVISIONS. MONTH OF NOVEMBER, 1914, COMPARED WITH MONTH OF OCTOBER, 1914

Freight Service.

	Fast freight				Slow freight				Local freight			
	Eastbound		Westbound		Eastbound		Westbound		Eastbound		Westbound	
	November	October	November	October	November	October	November	October	November	October	November	October
Train miles	3.283	3,484	4,954	7,576	8.485	9,177	6.152	4.880	2,880	3.240	2.933	3.240
Locomotive miles	3.283	3.486	8,042	11,128	16.529	18.038	11.269	9.824	2,956	3.321	3.012	3.321
Loaded car miles	130.147	140.202	159.377	219,435	484.644	529.559	203.556	209.889	29.965	33.893	32.990	37,339
Empty car miles	335	203	60,545	106,046	57.346	59,801	184,978	177,831	16.304	16.339	12.072	20.456
Caboose miles	3.283	3.484	4.954	7,576	8.485	9,177	6.152	4.880	2,880	3,240	2.933	3.240
Ton miles	4,399.743	4,589.492	5,941,893	8,677,627	21.121.401	22,885.161	10,496.232	10,448.521	1,301.163	1,414.569	1,432,065	1,702.877
Kw-hr. used	108.749	112.033	186.401	265.088	566.983	571,972	340,830	294,602	118,423	110,757	106,650	114.828
Locomotive miles per train mile	1.00	1.00	1.62	1.47	1.95	1.97	1.83	2.01	1.03	1.03	1.03	1.03
Loaded car miles per train mile.	39.64	40.24	32.17	28.96	57.12	57.71	33.09	43.01	10.40	10.46	11.25	11.52
Empty car miles per train mile.	1.10	1.06	13.22	15.00	7.76	7.52	31.07	37.44	6.66	6.04	5.12	7.31
Ton miles per train mile	1,340,16	1,317.31	1,199.41	1,145.41	2,489.26	2,493.75	1.706.15	2,141.09	451.79	436.60	488.26	525.58
Ton miles per locomotive mile	1.340.16	1,316.55	738.86	779.80	1,277.84	1,268.72	931.43	1.063.57	440.18	426.55	475.45	512.76
Percentage of tonnage to rating	96%	95%	......	......	94%	93%	......	......	......	......	......	......
Ton-miles per hour	26.779	27.335	19,109	18,092	26,008	27,912	18.637	23.297	2,614	2,679	3,423	3,622
Average speed (m. p. h.)	19.98	20.75	15.93	15.79	10.45	11.19	10.92	10.88	5.79	6.14	7.01	6.89
Kw-hr. per train mile	33.12	32,16	37.63	34.99	66.82	62.32	55.40	60.37	41.12	34.18	36.36	35.44
Kw-hr. per locomotive mile	33.12	32.11	23.18	23.82	34.30	31.71	30.24	29.99	40.06	33.35	35.41	34.58
Kw-hr. per car mile	.81	.78	.83	.80	1.03	.96	.86	.75	2.41	2.07	2.22	1.88
Kw-hr. per 1000-ton miles	24.72	24.41	31.37	30.54	26.84	24.99	32.47	28.20	91.01	78.29	74.47	67.43

Ton-miles are based on weight of trailing load.
Percentage of tonnage to rating is found by dividing the total tonnage of trains as they leave Harlem River by the rating of locomotives hauling those trains.
Ton-miles per hour is found by dividing ton-miles by the total running time of trains between terminals.
Average speed is found by dividing train-miles by total running time of trains between terminals.

Operating Costs.

	Locomotive repairs		Power		Locomotive supplies		Engine house expenses		Enginemen		Trainmen		Total	
	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.
Cost per train mile (cents)	15.51	15.98	28.51	27.90*	0.54	0.63	0.48	0.58	10.66	10.44	17.83	17.46	73.53	72.99*
Cost per locomotive mile (cents)	9.69	10.19	17.82	17.79*	0.34	0.40	0.31	0.37	6.67	6.66	11.14	11.13	45.96	46.54*
Cost per 1.000-ton miles (cents)	9.95	10.16	18.30	11.73*	0.35	0.40	0.31	0.37	6.84	6.63	11.45	11.09	47.20	46.38*

*Revised

TABLE XX. THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD COMPANY.

STATISTICS OF ELECTRICAL OPERATION—NEW YORK AND SHORE LINE DIVISIONS. FOR THE MONTH OF NOVEMBER, 1914, COMPARED WITH THE MONTH OF OCTOBER, 1914

Line and Equipment failures.

Line failures.

	Catenary insulator failures				Dead-end failures				Other-line failures				Equipment failures				Signal failures				Outside interference				Failures of employes				Total failures			
	Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.	
	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay
Between Woodlawn and Stamford	1	22	1	14	..	..	..	..	1	..	1	8	..	..	1	143	..	..	1	..	2	..	3	..	..	..	..	..	4	22	7	165
Between Stamford and New Haven..	2	..	..	..	..	..	..	..	3	41	4	47	6	141	5	23	1	15	..	..	2	..	..	..	..	..	..	..	14	197	9	70
On New Canaan Branch	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
On Harlem River Branch	..	..	..	..	..	..	..	..	1	13	1	7	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1	13	1	7
In Yards....	..	..	..	..	3	..	1	..	2	7	4	..	4	28	1	..	..	..	..	..	..	..	..	..	1	..	..	..	10	35	..	..
Total..........	3	22	1	14	3	..	1	..	7	61	10	62	10	169	7	166	1	15	1	..	4	..	3	..	1	..	..	..	29	267	23	242

Equipment failures

Class of service	Heated parts		Broken parts		Grounds		Miscellaneous		Total failures		Miles per failure		Minutes detention per failure	
	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.
Passenger..................	1	4	2	1*	20	25*	12	6	35	36*	7,071	7,328*	11	13*
Freight	1	2	1	2	3	2	0	1	5	7	13,183	9,506	56	60
Switch	0	0	0	0	0	0	0	0	0	0	40,964	39,624	0	0
Multiple..................	3	0	2	1*	2	0	11	11	18	12*	3,554	4,331**	18	7*
Total	5	6	5	4*	25	27*	23	18	58	55*	7,213	7,672*	17	18*

DISCUSSION ON "CONDITIONS AFFECTING THE SUCCESS OF MAIN LINE ELECTRIFICATION," (MURRAY), PHILADELPHIA, PA., JANUARY 20, 1915.

(*Subject to final revision for the Transactions.*)

Alfred W. Gibbs: While recognizing the merit of the paper and its frankness throughout, I call attention to a few points where it is not sufficiently explicit, or with which I do not agree.

As for the first, I allude especially to the tendency of cities to require electrification through their limits, usually for the purpose of eliminating smoke. While it is true that the inhabitants of a small community may be as much inconvenienced as those of the largest city, it must be recognized that this demand, if fully carried out, means the establishment of as many steam locomotive terminals as there are separate lines of road leading into the city, the alternative to this being the electrification of the whole line. These local terminals would involve not only a heavy capital outlay, but a continued charge to expenses, due to the increased cost of the additional organizations and the less efficient use of the labor and equipment. This is properly a charge to electrification, and a heavy one.

Mr. Murray is not quite fair in his criticism of the engineers who are responsible for the introduction of the direct-current system into the large terminals in New York City. It must be remembered that a long period of agitation had preceded the determination to electrify. The electrification was to avoid the objection to steam operation into the heart of a great city, and the first condition was that it should be a success from an operating standpoint. Is it surprising that the engineers in charge should turn to methods which had been thoroughly tried out? In at least one case the proposal to adopt the alternating-current system of transmission was not seriously advanced until after a very large outlay had been incurred for direct-current operation, a large part of which would have had to be absolutely thrown away to introduce the new system—and that untried on a large scale in this country. It must be remembered, further, that any serious operating failure would have jeopardized the whole investment and put back electrification for years. The engineers did not then have to settle the question of future extension of electrification. There was not then, and there may not be for a long time, any necessity to consider the question of future road electrification. By that time the air will have cleared considerably. It must be admitted that the operating results in New York have fully justified the engineers responsible.

I criticize, also, the statement that one pound of coal burned under the boiler of a central power plant will develop twice the drawbar power that the same amount of coal will produce when burned in a locomotive firebox. Proper allowance has not been made for the improvement in the modern steam locomotive with more liberal boiler capacity and with superheat. As an example,

I have a record of coal per drawbar horse power for 27 tests of one locomotive on the locomotive testing plant at Altoona. It shows:

2.5 to 3 pounds	12 tests
3 to 3.5 pounds	7 tests
3.5 to 4 pounds	3 tests
4 to 4.5 pounds	1 test
4.5 to 5 pounds	4 tests

These are the rates when running, added to which are certain standby losses at terminals.

The figures for the coal per kilowatt-hour at Cos Cob, as given by Mr. Murray, when reduced to drawbar horse power for the locomotive, do not justify the statement of relative efficiency.

There is great difficulty in arriving at a fair basis of comparison between steam and electric operation. For road locomotives and through electric operation the problem is the simplest. For switching service, where the steam locomotive may waste more steam at the safety valve that it uses in the cylinders, the problem is very different. This part of the paper covers one of the greatest advantages of the electric operation.

In the table giving the cost of power the total costs are not given. Operation and maintenance account for 0.511 cent; fixed charges, including taxes and insurance, amount to 0.180 cent. No allowance is made for depreciation in the form of obsolescence in the power house and its equipment. From data of somewhat similar power houses, I should say that the fixed overhead charge, including depreciation, would be nearly double the figure given, say 0.35 or 0.4 cent., in the inverse ratio to the output. I regard this part of the expense account as a most important part of the accounting; otherwise, the time comes with startling suddenness when you have obsolete equipment, with insufficient reserve to replace it.

While making these criticisms, it is but fair to recognize the courage of those responsible for the electrifications described in this paper and preceding ones.

The paper is, in my judgment, very instructive, and all the more so because no claim is made for the 100 per cent perfection which we never realize.

George R. Henderson: Mr. Murray's paper on main line electrification will stand out as a "classic" giving, as it does, actual figures for cost operation on an alternating-current line. Several years ago Mr. W. J. Wilgus gave similar data for the direct-current lines of the New York Central. Both of these papers show that "uniformity" of traffic is just as important as "density" of traffic, otherwise the overhead charges of the power plant, which must be abnormally large, will more than "eat up," any saving due to fuel consumption, repairs, and labor, as the plant must take care of *peak loads*, and these can only be "smoothed out" when the traffic is uniform. As

one hundred dollars per kilowatt will hardly cover power house and transmission lines, the importance of this observation will be obvious.

The fuel saving is stated as 50 per cent for a fixed drawbar pull, yet it must be borne in mind that this comparison is made with the old type of saturated steam locomotives, and modern steam engines, fitted with superheaters, will reduce this ratio very considerably, say to 65 per cent the amount of coal for such a locomotive as would be built today.

The fact that electric locomotives cost about three times as much as a steam locomotive of similar power must not be overlooked, also the flexibility of service of the latter is very important, as it may be transferred to any division desired owing to traffic conditions, and is not tied to a particular section whose limits are the lengths of the conductors leading from the power house. This is of prime importance to roads carrying intermittent business, such as live stock, which may have a week's work consolidated into a single night, or on the ore ranges in Michigan, which deliver cargoes to lake boats only during the period of navigation. Under such conditions the overhead charges would be out of all proportion to the work accomplished, and the electric locomotives would be idle a large part of the time, as they could be used only on electrified divisions.

However, we are glad to note that Mr. Murray does not wildly and enthusiastically proclaim electrification a " sure cure" for all evils, regardless of environment and operating conditions, as did some electrical experts a few years ago, and the conservatism for which he pleads will surely benefit the whole problem of electrification, by insuring the large expenditures chargeable to capital only where they will produce remunerative returns from operation.

E. H. McHenry: Mr. Murray strikes a very important keynote in the opening paragraphs of his interesting paper, in referring to the two-fold necessity for satisfying the requirements of both the public and the railroad as the touchstone of success.

The first requisite in the interest of the public may be fairly claimed as already satisfied, but the greater task of insuring adequate returns to the railroads upon the large capital investments required for conversion from steam to electric traction is as yet far removed from the state of an exact science. As stated by Mr. Murray, there are many places where electric traction could now be installed with profit, but the ability and ingenuity of the engineers will be taxed to the utmost degree in further widening and enlarging the present commercial field of application. The progress of recent years in the development of the art all tends in the right direction, as with experience and a clearer perception of the governing principles, the commercial efficiency of the invested capital grows greater, and there is no reason to doubt that the past progress will be continued in the future, with

the result of greatly extending the present limits. With the growing tendency toward the consolidation of the best features of all the divergent systems into one system of greatest combined merit, the so-called war of the systems is already nearly at an end, and even now it will be found that there is more to be gained by a study of the possibilities afforded by the new method of train propulsion in securing the closest adaptation of its many points of merit to the operating requirements than by any probable difference between rival systems. There is room for much optimism in this general direction, although many cases will arise of special difficulty, in which the community or that part of the public most benefited by the improved facilities, are least able or least willing to pay the cost of the service, as in the case of communities using costly passenger terminals, and unless some satisfactory method can be devised for spreading the cost of such service over a city or a state substantially in the form of a tax, no practical solution of this difficult problem will be clearly apparent. In electrification, as in all other branches of engineering, the highest art will be shown by " the ability to make a dollar earn the most interest."

C. Renshaw: As a traveler climbing a mountain will often not realize the height he has attained until, pausing, he looks back over the route he has traversed, so, although from the beginning I have followed the New Haven electrification through its various stages, the summary which Mr. Murray gives of the electric mileage, equipment, and activity to which the road has now attained has impressed me particularly.

The application of electricity to the operation of every class of passenger, freight, and shifting service on an entire engine division of one of the busiest trunk line railroads of the country is an achievement that stands without a parallel in the entire world. It should be particularly gratifying, not only to those who are interested in electrical matters, but to the general public as well, that the undertaking is proving an economic as well as a technical success.

No less notable than the achievement itself has been the policy of the railway company in giving so freely to the engineering public the full results of its investigations and experience, not only with regard to its successes, but—what is of perhaps greater utility and certainly of greater rarity—with regard to its difficulties. The costs and other data which Mr. Murray has included in this paper form a valuable addition to the previous contributions which he has made.

As might be expected from experience with any original enterprise, Mr. Murray estimates that the electrical plant of the New Haven road, with the ten years' experience in construction and operation, now available, could be reproduced today for not more than 60 per cent of its original cost. It should be gratifying to all, however, that he also states the financial return will ultimately be sufficient to justify the actual expenditure to

date, so that the courageous pioneer will not be a loser. Some road, he says, had to make the first break into the dark, but, from the data assembled, future results in the application of electricity in heavy trunk line territory can be predicated on assembled facts and not predicted from hypothetical analysis.

In considering the economies over steam operation, by means of which electrification can justify the investment which it requires, Mr. Murray puts the matter very simply by pointing out that these economies are normally of three kinds; *i.e.*, saving in fuel, saving in motive power maintenance and repairs, and saving in train-miles.

Broadly speaking, he says the costs of the first two items under electrification will be one-half the cost under steam operation. The saving in train-miles, however, depends very largely on local conditions and cannot well be generalized. Success in electrification, therefore, is primarily dependent upon density of traffic. This reduces the matter pretty well to its lowest terms and should help eliminate some of the mystery with which the savings to be effected by electrification have apparently heretofore been surrounded in the minds of many railroad operating officials.

A detail in the paper which deserves particular comment is the fact which is pointed out that an electric locomotive, like an over-willing horse, may work itself to destruction if permitted to do so. While it is perfectly possible to keep the cost of maintenance and repairs at one-half those of steam locomotives, under conditions most favorable to steam operation, Mr. Murray says it is only by the most rigorous and careful inspection and conformity to proper rules of operation that this can be done.

This fact is one of the most difficult to impress upon the minds of steam railroad operators, and it is to be hoped that the figures of 8.6 and 10.6 cents per mile for the maintenance and repairs of the general average of New Haven locomotives, as compared to the average of 3.96 cents per mile for the ten locomotives which have been properly overhauled, will have some effect in bringing about a more thorough realization of this important matter. Incidentally, this figure for the maintenance and repairs of ten locomotives, making 466,524 miles in the seventh year of their age, is a remarkable commentary on the reliability of such equipment when handled intelligently.

The paradoxical action of heavy freight trains in steadying the power house load instead of causing an increase in the peaks, as it was feared they would do, is also of interest. The fact that these trains, by dropping the voltage slightly, when drawing heavy accelerating currents, naturally cause other trains moving at high speed in the neighborhood to automatically reduce their power requirements, is readily appreciated when once noted, but is one of the many items brought out by actual experience which are often overlooked in advance calculations. Fortunately, in this case the unforeseen item is one which produces

a favorable rather than an unfavorable effect on the operation of the system.

Many other items which Mr. Murray has set forth are also worthy of comment, and the entire paper forms a valuable contribution to the subject. We hope that it may serve as an inspiration to other engineers in active touch with the operation of similar properties to present their experiences with equal freedom for the general benefit of the art.

F. E. Wynne: Mr. Murray's paper is a very valuable contribution to the literature of electric railroading, not only on account of the operating data which it contains, but because of its clear exposition of the broad principles to be considered in deciding whether an electrification will be successful. In the past electrical engineers have been accused (and to some extent rightfully so) of advocating wholesale electrification of steam railroads without regard to the measure of success which might be expected. It is therefore very pleasing to find a representative electrical engineer taking the stand that an electrification is only justified when it is an assured success from the standpoint of all parties concerned.

The figure of $15,000,000 given as the expenditure for electrification of the New Haven Railroad to date indicates that the expenditure has been $120,000 per unit of motive power and $30,000 per mile of single track. Complete electrification of the New York-New Haven division will be accomplished without additional expenditure for trolley construction (which is a very large proportion of the total), and consequently these unit figures will be somewhat changed. The total expenditure per unit of motive power will gradually decrease and that per mile of single track will increase to some extent because of the large number of electric engines in service without increase in the mileage of the electric zone.

The further statement that the present plant could be reproduced at the present time with better operating results for not more than 60 per cent of the actual cost to date, indicates that for an installation similar to the New Haven the total cost may be made less than $70,000 per unit of motive power, while the cost per mile of single track will be in the neighborhood of $20,000. These figures, as noted by Mr. Murray, represent the cash outlay, and in determining the net cost of electrification they will be reduced by the credits for steam equipment replaced, etc.

The figures given for mileage show that passenger locomotives average approximately 170 miles each, daily, and that only 22 per cent of total number of passenger trains have the full run of seventy-three miles. This daily mileage per locomotive is comparable to that secured from electric cars operating in rapid transit and heavy interurban service. It therefore seems reasonable to assume that when all through trains are electrically operated the average daily mileage per locomotive may be materially increased.

Similarly, the multiple-unit motor cars show an average of eighty-four miles each, daily. This is relatively low, but is undoubtedly due to the fact that local trains are bunched in the morning and evening rush hours to a greater extent than is ordinarily found. This low mileage, together with the fact that over half of the total multiple-unit trains operate with only one trailer per motor car, indicates that the railroad is not yet getting the full benefit of the rather large equipments on the motor cars.

The figures given in connection with the operation of the switching engines illustrate the remarkable reliability and operating economy of electric locomotives in this particular class of service. Such results lead us to believe that the field for the electrification of railroad yards is a large one and that considerable progress in this direction will follow a full appreciation of the success which may be expected. As density of traffic is one of the largest factors in determining the advisability of electrifying main lines, so the desirability of yard electrification will largely be determined by the degree of congestion existing. In such installation the initial expense may be reduced to a minimum where central station power is available.

Mr. Murray states that electrification very quickly increased the reliability of operation to some three or four times that of the steam operation it replaced. We do not altogether understand what is the measure of reliability used in making this comparison, but assume he means that the number of failures were from one-third to one-fourth as many as were encountered during steam operation for a similar period.

In connection with Mr. Murray's statement that maintenance and repairs on electric locomotives amount to approximately one-half those required for steam locomotives with equal weight on drivers, I should like to ask whether operation in equal service also should not be part of the basis of comparison.

The remarks regarding the differences in the natures of electric and steam engines are particularly pertinent, and Mr. Murray's plea for electrically-trained men in the administrative department of electrified steam railroads points out one of the things which is of the highest importance in securing the fullest measure of success in electrifications.

It is interesting to note the results secured in connection with energy consumption, as these closely check the accuracy of calculations made in connection with this service, thus illustrating the fact that the energy consumption with electric operation can be very closely predetermined where trains are operated on a steam railroad basis; that is, with definite schedules and definite stops. The figures given show, further, how rapidly the consumption of energy increases with the increasing number of stops as indicated by the several classes of service. Since the electrical equipment is merely apparatus for converting electrical into mechanical energy, it follows that with increased unit en-

ergy consumption increased work is required of the electrical equipment, and therefore electric locomotives will safely handle much greater tonnages in through service than in local service. They will also handle greater tonages at moderate speeds than can be operated at high speeds.

The information regarding the improvement of load factor and smoothing out of the curve of power station output with the addition of trains (even though those trains were comparatively heavy) illustrates a principle which has been found to exist in connection with city and interurban electric railways namely, that the peak load on the system increases less rapidly than in proportion to the increase in number of cars or trains operated. However, in city and interurban systems this is probably due more to the fact that, as the number of cars operated increases, a smaller proportion of the total are starting simultaneously, rather than to the fly-wheel effect of the moving cars. We are inclined to the opinion that with further increase in the number of trains electrically operated by the New Haven Railroad some benefit in the improvement of load factor and reduction of peaks will be secured from this source, as well as from the fly-wheel effect of the moving trains.

The reduction in cost of the trolley construction which has been made since the initial installation shows great progress in the right direction. However, we believe that it is not yet sufficiently low to represent maximum all-round economy. This belief is strengthened somewhat by Mr. Murray's statement of the extraordinary reliability of the overhead construction in stormy weather. This great degree of reliability leads us to question whether part of the cost of the overhead construction may not be due to its being designed with an unnecessarily great factor of safety.

In connection with Table XVII, only interest, taxes, and insurance are specified as fixed charges. I should like to ask whether a depreciation allowance is included in the figures given.

I feel that the Institute is to be congratulated upon securing the presentation of such an able paper, and trust that its author may continue to make public his valuable data regarding the principles of railroad electrification, to the end that electric operation of steam railroads may be extended and may be attended by the greatest success.

Philip Torchio: The growth of large electrical undertakings has been the evolution from small beginnings. In the case of railroad electrification, however, the problem has been quite different. With an established heavy traffic which does not allow of interruption or delays, a new system of traction is to be substituted, requiring radical structural changes all along the line and an entire new system of power generation and distribution.

The engineers confronted with the problem have attacked it in a comprehensive and thorough manner, developing complete

systems as self-sustaining and autonomous as the progress of the art allowed them to accomplish at the time. Mr. Murray has described the operation of a system which really went a step further and anticipated the progress of the art by many years. The importance of this epoch-making " experiment " is naturally very great.

The author emphasizes the point that the experience of the New Haven will benefit the other railroads in solving their problems of electrification. In this connection I wish to call attention to the item of investments in power houses and power-transmitting lines, which in all the original electrifications were assumed as a necessary part of the equipment, but which in late years the railroads have found more economical to omit from their investment, substituting purchased power delivered to them by central-station power companies. The New Haven has purchased from the New York Edison Company all the power required for its western section of the alternating-current lines and terminals. The Pennsylvania Railroad has purchased from the Philadelphia Electric Company the power for the electrification of its main line from Philadelphia to Paoli and for its other contemplated extensions around Philadelphia. The London, Brighton and South Coast Railway Company buys current from the London Electric Supply Corporation, Ltd. The Chicago, Milwaukee and St. Paul Railway and the Butte, Anaconda and Pacific Railway buy power from the Montana Power Company.

Along every large railroad where the heavy traffic would warrant electrification there is, or can be made readily available abundant supply of electrical power from power companies. These companies, by averaging the power demand from a great diversity of users, reap economical advantages in investment and in generation and distribution of power which the railroad cannot secure under independent generation. I wish to call attention to this phase of the problem, as the saving in investment in stations, substations and transmission lines may represent a sensible item in the investment of railroad electrification.

The central stations, besides offering investment and operating advantages, can furnish, in addition, a more reliable supply of power, because they command the best knowledge of the art of electricity supply, which is their exclusive and specialized business.

W. A. Del Mar: This paper is interesting not only as a statement of operating results with the single-phase system of traction but also as a basis of comparison between steam and electric traction. Indeed, so nearly equal are the principal electric systems from an economic point of view that we may well afford to neglect their rivalry in view of the more vital rivalry between steam and electricity. I believe that the " battle of the systems " was largely caused by the advocates of each system being so carried away by enthusiasm as to be unable to tell the whole truth, whether in defending their own or

criticising the others. Here, at last, we have a presentation of operating results, making it unnecessary to base conclusions upon specious arguments about details.

It is unfortunate that the operating costs are given for only two months of the year. The results would have been more valuable if they had been based upon a complete year, as it is almost impossible to select two really representative months, especially in view of inevitable variations of maintenance costs of equipment. The omission of the annual fixed charges is also to be regretted, as it is well known that the running charges can be made less with electric than with steam traction, but it is not always clear whether the fixed charges added by the electrical plant will destroy the favorable balance due to operating economies. Various cost data are presented, but in such form as not to be available for calculating fixed charges. We do not know, for example, whether the $15,000,000 expenditure mentioned by Mr. Murray includes the cost of reducing telephone disturbances and of altering the right-of-way to conform with electrical requirements.

One cannot help being appalled at development charges amounting to 40 per cent of the entire investment, as one would infer from Mr. Murray's statement that the present system could be replaced for 60 per cent of the original investment. An interesting feature about the installation has been the development from the complex to the simple in mechanical details, and *vice versa* in the electrical features.

Examining the operating costs with the view of comparing them with steam operating results, one is confronted by a series of questions which, if unanswered, will render such comparison difficult. Having gone to great trouble to segregate and clearly present the operating costs, Mr. Murray proceeds to obtain unit costs by dividing these operating costs by car mileages and train mileages of unspecified nature. It is to be hoped that Mr. Murray will state the nature of the mileages with greater detail, particularly as to whether they include yard switching and light locomotives. These two items may easily amount to 15 per cent of the entire mileage.

The fixed charges given for the Cos Cob power station appear to be very low. It would be interesting to know whether they include depreciation.

An interesting feature of the New Haven installation is the use of meters on the locomotives. This enables an intelligent estimate to be made of the relative cost of different classes of service, such as passenger locomotive, freight, and multiple-unit. Meters on locomotives are not very accurate, due to vibration, but it is interesting to note that, provided the vibration is impartial with respect to making the meters read high or low, the probable error in the aggregate reading will be quite small, due to the large number of locomotives. Thus where there are

100 locomotives a possible error of 20 per cent in each meter will cause a probable error of only $\frac{20}{\sqrt{100}} = 2$ per cent in the total.

Electric railway men should feel very grateful to Mr. Murray for this paper, which will long be consulted as a classic upon a great engineering topic.

R. H. Wheeler: In this paper there comes a boon to those interested in the application of electricity to train movements, in the practical definitions of conditions which affect the success of a railroad electrification, supplemented by copious data resulting from an extended period of operation. The haze from the "shots" of the "battle of systems" now clears away from the single-phase side of the field, showing an interesting array of results achieved.

Two points, from the many ably put forth, appeal to me for special emphasis. These are vital to the success and quantity of success, which latter is the chief "lure" of electrification.

First.—The careful analysis and choice of a form of electric power which may be standardized for all classes of train service on that road.

Second.—The "inheritance" to electric operation of "steam-trained" operators.

Under electric operation the power plant is separated from the locomotive, and it is evident that the economy of energy transmission, from its source to the wheels of the engine, is paramount. The overhead contact wire lends itself very readily to this transmisson duty, in yards, terminals, on the road, and elsewhere. For reasons of high economy of transmission and diversity of transformations, Mr. Murray suggests that this wire be energized with 11,000 volts single-phase, 25-cycle power. By the use of the mercury-arc rectifier the admirable qualities of the series direct-current motor can be retained. This motor is especially desirable where the "density of traffic" factor is highest, as in suburban and terminal electrification, on account of its accelerating capabilities and weight economies, both in itself and its control. However, to carry about a rectifier upon the class of equipment employed in terminal service, even if rectified single-phase current were suitable, would impose a serious handicap in both weight and control complication. Rectified single-phase current is not ideal for direct-current motors of the usual design, requiring increased thermal capacity and thus weight. These reasons militate against the "standard" proposed as suitable for all classes of train service.

However, by placing the rectifier in the roadside substations and taking advantage of the economies and freedom of disturbance to other local circuits of a balanced three-phase, 60-cycle supply, another "standard" results which supplies, over the overhead contact wire, power at 3000 volts direct current, and which has the desired essentials of transmission economy and standardization of motive power equipment. In the case

of heavy grade divisions operated by rectifier substations, engines arranged for regeneration would be employed. This second " standard " is offered to emphasize Mr. Murray's definition of the successes arising from a choice of energy which can be standardized. A railroad which, in its initial electrification, utilizes a system which is capable of being extended through successive increases of electrically-operated territory has gone far to ensure successful electrification.

With the figures Mr. Murray presents, indicative of the successful operation of the New Haven motor cars and a-c. d-c. engines since the last overhaul in a well-appointed maintenance shop, it is evident that the straight alternating-current engines will show greater economies. When the data are available from the Butte, Anaconda and Pacific Railroad, Chicago, Milwaukee and St. Paul Railroad, and Canadian Northern Railway, giving results of operation, especially as the latter is to employ 2400-volt motor cars, another decisive step towards standardization can be made.

Secondly, I wish to emphasize the important part that " heredity " plays. Mr. Murray states that a thorough understanding must be had of the fundamental differences between steam and electric operation. Electric operation is a more exact science than steam operation, since a great many of the variable factors are removed. Chief of these, the power generating plant, is removed from the hands of the fireman, and he cannot now produce more power to get an overload engine over the road. Certain rules and axioms the officials of the operating department must appreciate in adapting themselves to the era of electrification.

As well, the proper care and thorough inspection of electric equipment should be insisted upon and the long life resulting from renewals and not repairs be gained. It takes thorough investigation and time to care for such equipment, and in the early stages a little more leeway should be given the shopmen. Cooperation in these things will produce the economies which make an electrification successful.

W. S. Murray: The writer takes this opportunity of expressing his appreciation of the many interesting points and suggestions that have been brought out in the discussion of the paper.

Before specifically commenting on the individual discussions, the writer desires to draw attention to an (apparent) error in the paper, which appears in Table XVII, under the statement covering the output of the Cos Cob station. In that statement the fixed charges are named as 1.8 mills per kw-hr. This statement is based upon certain discounts allowed by the railroad company on installation charges, and also does not include depreciation. For outside comparative purposes, however, the rate of 1.8 mills should be changed to 2.9 mills, the latter figure being based upon an eleven per cent rate on the total

investment involved, carrying with it interest, insurance, depreciation, and taxes. The total cost, therefore, for current would become 8.01 mills per kw-hr. instead of the rate named in the paper of 6.91 mills, the former and larger figure being then in form, as previously stated, for comparative purposes.

I am indebted to Mr. H. P. Davis, vice-president of the Westinghouse Electric and Manufacturing Company, for his valuable discussion, and it is hardly necessary for me to point to the fact that not a little of the success in the application of high-tension alternating current to heavy traction systems is due to Mr. Davis. In particular we are indebted to Mr. Davis for the system of control that is used for electrical sectionalization, and, while the New Haven system now in service has been modified considerably to conform to the rearrangement of its circuits to reduce to a minimum electromagnetic induction, the earlier and basic elements which were worked out largely under the suggestion and cooperation of Mr. Davis are found in the system now controlling our entire lines.

Mr. Davis's long connection with the development of heavy electric railway equipment lends authority to his voice in commenting on the proper treatment which should be accorded electrical equipment. It might be said of electrical as compared with steam equipment, that *it is possible to get twice as much out of it and it is four times as different*, and the brains and fingers that are to handle the electrical equipment should have an electrical rather than steam instinct governing them, for the rapid progress and success of the application of electricity to heavy traction railways will largely depend upon the recognition of these simple facts.

Of the various departments of a railroad, covering respectively executive, traffic, transportation, legal, operating, and engineering matters, it were natural and seemingly logical to assign an electrification problem to its engineering department, and yet the advance of the art in the application of electricity for heavy traction purposes has been so rapid that I venture the opinion that ninety per cent of the chief engineers of all the roads in this country, being so perfectly unacquainted with the underlying principles of the generation and application of electricity, would shrink from such a responsibility. It is to be noted that a few roads have placed their engineering department under the jurisdiction of their operating department, under which arrangement an assignment of the problem to the engineering department jeopardizes still further the desired result. The railway company will do well, therefore, when it decides to make so radical a change in its motive power, involving millions of dollars, to assign that responsibility solely to a man qualified to assume it, and also to see to it that his hands are not tied by having to report to officers in the engineering and operating departments, who are unacquainted with the governing principles of electricity; indeed, on the contrary, it is my

opinion that these departments should be requested by the president to cooperate to the full with the officer responsible for the work, thus clothing rather than robbing him of the authority so essentially necessary in producing an *electrical* plant to accomplish an *electrical* result.

As the above is true in the matter of electrical engineering and construction, it is to a very great extent true in the matter of operation, and, as pointed out in the paper, while no radical change is necessary in the general railroad organization of to-day, I cannot too greatly emphasize the absolute truth that when a railroad company has adopted electricity to be its motive power the operating officials should state the *schedules* and *consist* of trains, and then abide by the decision of the electrical officer (whose duties might be defined as " in charge of electrical engineering and construction and the features of electrical operation ") as to what power, both generative and motive, is necessary.

In the past there has been an appalling attitude on the part of officials of some steam railroads electrifying—rather than welcoming the selection of electrically-trained men for positions such as superintendents of electrical shops, road foremen of electric engines, master mechanics for electric engines, to insist that these positions be filled by men who have occupied seemingly analogous positions under steam locomotive conditions, notwithstanding their past environment, experience, and adaptability to the new and different conditions confronting them make them unfit, both from a safety and economic standpoint, to serve. Railway managements are now waking up to these facts, and in the last year great improvement in the electrical *personnel* of the operating departments has resulted. There is much along these lines to be accomplished yet, and dire necessity, as much as anything, has brought about the real and final awakening of a differentiation between electrical talents that apply and those of steam that do not. This information is too vital, and, indeed, as it constitutes the very rivets and gusset plates of the electrification bridge over which we are crossing to more economic, safe, and satisfactory railroading, it has a fitting place here. It has been a strenuous past; the bills have all been paid, and as sure as they represent the millions of dollars lost in the past, so do they equally represent the millions of dollars to be saved in the future, and so at least we can say it has taught us " how not to do it."

Referring to Mr. McHenry's comments: It has always seemed to me that electrification has been an advantage to " the many" at the expense of " the few." While it is true that electrification for *economy's* sake bids fair to preëmpt the use of it for *necessity's* sake, still it is fair to believe that the consideration of electrification of city terminals carries for the present a more popular justification, and if it can be proved beyond doubt that the electrification of city terminals imposes a financial

burden upon the railroad, it would seem to me that Mr. McHenry's suggestions of an "outside" tax should find justification.

In Mr. George R. Henderson's valuable contribution to the paper an excellent point is made with regard to the uniformity of traffic being a most important adjunct in securing the economies of electrification. In nearly all the situations of electric power generation and distribution we seldom, if ever, hear of one wherein a 100 per cent load factor obtains. There are thus certain hours in a day, and in railroad work generally two such periods (if only the passenger service is operated by electricity), when the power requirements are at a maximum. It is thus seen that at all other times of the day and night full advantage is not being taken of the total electrical investment. Realization upon Mr. Henderson's suggestion is to a large measure accomplished by the electrical movement of freight as well as passengers, as the maximum power demand for the former can be made to follow at the time of minimum demand for the latter. Those who have studied the matter of load factors in their application to lighting and street railway properties have accustomed themselves to such figures as from 35 to 45 per cent and sometimes reaching 50 per cent load factor. I have no doubt it will be of interest to state that in plotting the combined load curves of the New Haven passenger, freight, and switching services without any rearrangment of the schedules as they are made up today a load factor of 75 per cent is secured, which figure, I am sure Mr. Henderson will agree, bespeaks the uniformity of the density of traffic at least in the New Haven case. It is apparent, therefore, that in the study of electrification equal consideration should be given to both freight and passenger movement.

With regard to fuel saving, if the economy of generating units remained fixed, it would be fair to grant Mr. Henderson's point with regard to the change of ratio from 50 per cent to 65 per cent. On the other hand, the thermal efficiency of generating plants is easily keeping pace with that of steam locomotives, and, granting this, there are no other constants or variables which will tend to alter the ratio of one or two in favor of the fuel economy of drawbar pull by central electrical stations *versus* steam locomotives.

Mr. Henderson's point with regard to the transfer of steam locomotive power to different divisions of a road where congestion may require is interesting; I can conceive, however, of a division electrifying, with economy, not inclusive of the financial credits due to the steam locomotives replaced, thus automatically providing steam locomotives for service in the congested districts. The principal value of Mr. Henderson's observation on this matter, to me, is in pointing out that every electrification is a study in itself, and in electrifying one division its effect may be felt in many different ways in other divisions.

I am indebted to Mr. F. E. Wynne for his unit analysis of investment cost. I think that he has transformed electrification investment into a very unique and interesting basis for consideration. His assumption with regard to the limitation of passenger locomotive and multiple-unit car mileages is entirely correct; the morning and afternoon suburban traffic to and from New York City, with its close headway, makes the problem of securing high car and locomotive mileage most difficult.

Answering Mr. Wynne's question as to the statement of increased reliability of operating when electric was substituted for steam service, I would advise that this was, as he surmised, upon a failure basis. A fair average for steam locomotive operation might be cited as 5000 miles per engine failure, whereas with electrical operation it certainly should be 12,000 and in a number of instances on the New Haven it has been as high as 18,000, and it is my understanding that both the Pennsylvania and the New York Central have reached figures higher than this, our own mileage having been lower than the others, due chiefly, I think, to the requirement of the dual a-c-d-c. operation.

I am entirely in agreement with Mr. Wynne that the maintenance and repairs on electric locomotives should be compared to those of steam upon the basis of equal service and weight on drivers.

Again I find comfort in Mr. Wynne's emphasis upon the high importance of securing the proper electrical administrative forces in the electrified zones of steam railroads.

Answering Mr. Wynne's inquiry with regard to Table XVII, as explained in my general note at the beginning of this discussion, no allowance was made for depreciation under fixed charges.

Mr. Philip Torchio's contribution is of great interest, and shows the trend and possibilities of large central-station power in the field of electrification. The introduction of an alien power to produce drawbar pull upon a railroad is certainly a departure from past practise. The acceptance of this practise hyphenates the name of the mechanical superintendent, and the central power stations who have relieved him of a part of his duties will do well to see that this new step is justified, and it can only be justified by a practically perfect continuity of service.

Many railroads electrifying will insist upon the internal control of their entire power, others will mingle purchased power with their own power, and, finally, still others will depend entirely upon purchased power. I see no particular difficulty arising in any one of these three arrangements of supply, and I have agreed with Mr. Torchio that the only true basis for a contract by a railroad for the supply of outside power will be that that power can be supplied with the same reliability as the power could be produced by the railroad company and at equal cost.

The higher thermal efficiency secured in the use of large generating units affords an opportunity for large central-station plants to sell power to railroads, a measure of the justifiable profit in this sale being in the difference in efficiency between the smaller generating station (required by the railroad) and that of the central station. Such an arrangement as Mr. Torchio has pointed out provides an economical supply of power, and at the same time obviates the necessity of the railroad company investing in this feature required for electrification. Indeed, and digressing for a moment, I will go a step further under Mr. Torchio's thought and say that in these days when railroads are so hard up for cash the "equipment trust" offers a relief in the matter of the purchase of electric motive-power equipment, leaving as the only cash investment necessary, on the part of the road electrifying, that incident to the cost of the distribution and contact system required for the operation of its trains, and such buildings or modifications of buildings as will cover the shopping requirements of the new electrical equipment.

Commenting on Mr. Alfred W. Gibbs's valuable contribution in the discussion: His first point is well taken, and has been long recognized as one of the serious capital and operating expenditures where the problem of electrification is applied to deviating lines entering a city, and unless, as Mr. Gibbs points out, each one of these lines is electrified throughout the entire division, it is necessary to arrange local terminals to permit a change from steam to electrical operation. Such a condition, for example, is manifest in the study of the electrification of the various lines of the New York, New Haven and Hartford, the Boston and Albany, and the Boston and Maine Railroads entering the city of Boston. As Mr. Gibbs advises, this is quite properly a charge to electrification, and a heavy one. On the other hand, large cities gridironed with their entering roads may have a density upon these tracks which will permit the terminal charges and still be within the economic limit of electrification. The tendency will be, of course, to electrify roads entering the cities upon which the greatest traffic obtains, and those having a lesser density will in turn be electrified as increased density justifies. The difficult financial situations in which the railroads of today find themselves are becoming better appreciated daily by the public, and it is safe to assume that, as density of traffic is the controlling factor in electrification, a city's people will see the justice of such a proposed procedure.

I fear my little remark with regard to the third rail "having gone to seed" has unwittingly lodged in Mr. Gibbs's vermiform appendix, and will necessitate a slight operation on my part. Let me hasten to withdraw any seeming attitude of criticism on my part with regard to the engineers who were responsible for the introduction of the direct-current system, particularly in the New York City terminals. That the Pennsylvania Railroad Company has adopted the overhead system for its Phila-

delphia electrification, I confess, offered partial grounds for the suggestion that the third rail was past its flowering stage.

Mr. Gibbs's table showing the economy of steam locomotives with more liberal boiler capacity and with superheat is most interesting. The note that Mr. Gibbs adds, however, that "*these are the rates when running, added to which are certain standby losses at terminals*," transforms "test" into practical conditions, and, as explained in my commentaries on Mr. Henderson's discussion, the improvement in thermal efficiency of central power stations can easily keep pace with any similar improvements in the steam locomotives. I feel sure that Mr. Gibbs will later find that my statement with regard to this matter is correct, and, if he does so, will take the first opportunity to withdraw his criticisms of my statement that "one pound of coal burned under the boiler of a central power plant will develop twice the drawbar power that the same amount of coal will produce when burned in a locomotive firebox." When I made the statement I had, of course, reference to the average conditions of practical operation.

As explained in the paragraph preceding my commentary on the general discussion, the figures for depreciation upon the Cos Cob power station were not included, and for comparative purposes they should have been allowed. Mr. Gibbs has named a rate of 0.35 cent, or 4 cents per kw-hr., as the amount that should apply, and it is to be noted that upon the basis of 11 per cent upon the total investment made, covering interest, insurance, depreciation and taxes, the figure 0.29 cent, while less, does not differ greatly from that suggested by Mr. Gibbs.

Mr. Wheeler discusses most interestingly two vitally important points in the matter of electrification:

(1) The form of electric power which may be standardized for all classes of train service.

(2) The inheritance in the electric zone of "steam-trained" operators.

With regard to (1), the question of the location of the rectifier on or off the locomotive will always admit of local analysis for the most economic result. Mr. Wheeler has pointed out some very interesting possibilities in this direction.

With regard to (2), the matter of electrical administration, I have already expressed myself at such length on this matter that it will be only necessary to acknowledge with interest Mr. Wheeler's concordant sentiments.

Mr. W. A. Del Mar has asked some very pertinent and interesting questions, which I am very glad to answer. With regard to the expenditures made to reduce telephone disturbances, and of altering the right of way to conform with electrical requirements, these were included in the general figure of $15,-000,000 mentioned in the paper. It is of interest, however, to note that past experience has indicated a proper method of laying out the transmission and distribution system whereby

automatic compensation for telegraph and telephone disturbance can be secured for a very nominal amount. For example, in the case of the electrification of the four-track lines between Stamford and New Haven, the arrangement of transmission and distribution for the most economic traction result proves the most efficacious for reduction of the telegraph and telephone disturbances.

It is of interest to note that Mr. Del Mar is appalled at the development charges of the single-phase system, and, while I am at a loss to understand how a "fact" can be presented in an "ingenious way," as an example of a reduction of costs, our strain insulators in 1907, when we first began the electrification, cost $63. Today, with factors of safety three times both the electrical and mechanical values they had in their original installation, the cost has been reduced to $7. A longer experience in the handling of work-train service and the administration of construction work upon those work trains are points along the curve representing 40 per cent in the reduction of construction, etc.

With regard to the four questions Mr. Del Mar has asked, I am glad to answer them as follows:

(1) Q. Do these mileages include or exclude yard switching?

A. The mileages given for both passenger and freight service do not include yard switching (*yard switching* is taken care of by yard switchers designed especially for that purpose).

I would advise, however, that the locomotive-miles as shown on line 2 of the operating statistics, in the case of both the passenger and freight service, include the mileage of locomotives in trains and also the miles "run light" between engine-houses and stations. In figuring the passenger operating costs, however, the mileage of engines "run light" between stations is also included, thus giving the total passenger locomotive-miles, and in figuring the operating costs on freight locomotives likewise the miles of light moves and the mileage of locomotives switching at way stations on the main line are also included. It would doubtless be of interest to Mr. Del Mar to know that we have added a third sheet of statistical information having reference only to yard switching mileage and yard switching costs, which sheet had not been inaugurated at the time the paper was written.

(2) Q. If they exclude yard switching, do not the operating costs appear unduly high? If they include yard switching, how is it estimated?

A. The above answer to Question 1 doubtless serves as an answer to Mr. Del Mar's second question. While agreeing to his statement that the costs are high, I only hope that I have made the reason for this clear, especially in view of the typical record of the costs of maintaining the ten engines which at the time of the paper had received a full overhaul in the new shops. As previously explained, some of these engines had run 300,000 miles without undergoing any general repairs.

(3) Q. Are light locomotive mileages included in train-miles?

A. The train-miles did not include the mileage of locomotives "run light," but have been recorded and are included in the total locomotive mileage in computing the unit cost per locomotive-mile both in freight and passenger service.

(4) Q. The fixed charges given for Cos Cob power station appear to be very low. It would be interesting to know whether they include depreciation.

A. As explained in the previous part of this discussion, they did not include depreciation.

Mr. Del Mar's point with regard to the negligible error of meter registration on locomotives is very interesting, and so far as we have been able to determine, the meters have been an accurate and valuable adjunct in the determination of the general distribution of power.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Approved by the Board of Directors, June 30th, 1915

TO TAKE EFFECT JULY 1, 1915

NOTE.

This edition of the Standardization Rules represents substantially the completion and clarification of the edition of Dec. 1st, 1914, although some important additions have been made.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

HISTORY OF THE STANDARDIZATION RULES

The first step taken by the Institute toward the standardization of electrical apparatus and methods was a topical discussion on "The Standardization of Generators, Motors and Transformers," which took place simultaneously in New York and Chicago on the evening of January 26, 1898. The discussion appears in the Institute TRANSACTIONS, Vol. XV, pages 3 to 32. The opinions expressed were generally favorable to the scheme of standardization of electrical apparatus, although some members feared that difficulties might arise. As a result of this discussion, a Committee on Standardization was appointed by the Council of the Institute, consisting of the following members:

FRANCIS B CROCKER, *Chairman.*

CARY T. HUTCHINSON	CHARLES P. STEINMETZ
ARTHUR E. KENNELLY	LEWIS B. STILLWELL
JOHN W. LIEB, JR.	ELIHU THOMSON

After a careful consideration of the matter and consultation with the members of the Institute and interested parties generally, a "Report of the Committee on Standardization," was presented and accepted by the Institute, June 26, 1899. Those original rules appeared in the Institute TRANSACTIONS, Vol. XVI, pages 255 and 268.

As a result of changes and developments in the electric art, it was subsequently found necessary to revise the original report, this work being carried out by the following Committe on Standardization:

FRANCIS B. CROCKER, *Chairman.*

ARTHUR E. KENNELLY	CHARLES P. STEINMETZ
JOHN W. LIEB, JR.	LEWIS B. STILLWELL
C. O. MAILLOUX	ELIHU THOMSON

This revised report was adopted at the 19th Annual Convention at Great Barrington, Mass., on June 20, 1902, and appears in the Institute TRANSACTIONS, Vol. XIX, pages 1075 to 1092.

In consequence of still further change and development in electri al apparatus and methods, it was decided in September, 1905, that a second revision was needed, and the following Committee was appointed to do this work.

FRANCIS B. CROCKER, *Chairman.*

ARTHUR E. KENNELLY, *Secretary.*

HENRY S. CARHART	CHARLES F. SCOTT
JOHN W. LIEB, JR.	CHARLES P. STEINMETZ
C. O. MAILLOUX	HENRY G. STOTT
ROBERT B. OWENS	S. W. STRATTON

This Committee held monthly meetings and carried on extensive correspondence with manufacturers, consulting and operating engineers and other interested parties, and as a result, presented its report at the 23d Annual Convention, held at Milwaukee, May 28–30, 1906. After considerable discussion the report was accepted and referred back to the Committee for amendment and rearrangement in form. It was then to be submitted to the Board of Directors for final adoption. In September, 1906, the following Standardization Committee was appointed:

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

A. W. BERRESFORD	CHARLES F. SCOTT
DUGALD C. JACKSON	CHARLES P. STEINMETZ
C. O. MAILLOUX	HENRY G. STOTT
ROBERT B. OWENS	S. W. STRATTON

ELIHU THOMSON

This Committee held monthly meetings, also sub-committee meetings, and carefully referred the rules as a whole, and each part of them, to the members of the Institute. The rules were also entirely rearranged as to form, and put in shape to facilitate ready reference to them and enable future revisions to be made without breaking up the logical arrangement. Thus amended the rules were submitted to the Board of Directors and approved by it on June 21, 1907. The Board also directed that the rules should be presented, as accepted by the Board, at the Annual Convention held at Niagara Falls, June 24 to 27, 1907, which action was taken by President Sheldon on June 26, 1907. By the Constitution which went into effect on June 10, 1907, this Committee has been made a standing Committee with the title " Standards Committee," consisting of nine members.

On August 12, 1910, the Board of Directors increased the size of the committee from nine to twelve members; on October 14 from twelve to fourteen, and on March 10, 1911, from fourteen to sixteen. The committee thus constituted is given below.

COMFORT A. ADAMS, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

H. W. BUCK	W. S. MOODY
GANO DUNN	R. A. PHILIP
H. W. FISHER	W. H. POWELL
H. B. GEAR	CHARLES ROBBINS
J. P. JACKSON	E. B. ROSA
W. L. MERRILL	CHARLES P. STEINMETZ
RALPH D. MERSHON	CALVERT TOWNLEY

This committee and several sub-committees held numerous meetings at which the general revision of the Standardization Rules of the Institute was considered. The complete Standardization Rules, as revised by this committee, were presented to and approved by the Board of Directors on June 27, 1911, at the Annual Convention held at Chicago, Ill.

During the following two years (1911-1913) the Standards Committee, somewhat modified and enlarged, undertook a radical revision of the Rules, particularly in connection with the important subject of Rating. In August 1913 the Committee was still further enlarged by the Board of Directors in order to permit of comprehensive sub-committees for the various parts of the work. The Committee thus constituted is given as follows:

A. E. KENNELLY, *Chairman.*
COMFORT A. ADAMS, *Secretary.*

SUB-COMMITTEE No. 1. ON RATING.

H. M. HOBART, *Chairman.*

JAMES BURKE
W. C. L. EGLIN
B. G. LAMME
W. A. LAYMAN
W. L. MERRILL
W. S. MOODY
W. H. POWELL
CHARLES ROBBINS
C. F. SCOTT
JAMES M. SMITH
CHARLES P. STEINMETZ
J. FRANKLIN STEVENS
PHILIP TORCHIO

SUB-COMMITTEE No. 2. ON TELEGRAPH AND TELEPHONE STANDARDS.

F. B. JEWETT, *Chairman.*

H. W. FISHER
F. F. FOWLE
R. H. MARRIOTT
J. H. MORECROFT
J. M. SMITH

SUB-COMMITTEE No. 3. ON RAILWAY STANDARDS.

W. A. DEL MAR, *Chairman.*

F. W. CARTER*
HUGH HAZELTON*
E. R. HILL*
H. M. HOBART
WILLIAM MCCLELLAN
HAROLD PENDER
MARTIN SCHREIBER*
N. W. STORER*

SUB-COMMITTEE No. 4. ON NOMENCLATURE AND SYMBOLS.

COMFORT A. ADAMS, *Chairman.*

LOUIS BELL
DUGALD C. JACKSON
M. G. LLOYD
H. PENDER
E. B. ROSA
A. S. MCALLISTER
R. H. MARRIOTT

SUB-COMMITTEE No. 5. ON WIRES AND CABLES.

H. W. FISHER, *Chairman.*

WALLACE CLARK
W. A. DEL MAR
W. C. L. EGLIN
E. B. ROSA
C. E. SKINNER
S. W. STRATTON

SUB-COMMITTEE NO. 6. ON RATING AND TESTING OF CONTROL APPARATUS.

L. T. ROBINSON, *Chairman.*

MORTON ARENDT
R. A. CARLE
C. H. SHARP
P. H. THOMAS
PHILIP TORCHIO

Sub-committee No. 1 had representation from the National Electric Light Association (Messrs. L. L. Elden, G. L. Knight, J. E. Kearns, and E. P. Dillon), from the Association of Edison Illuminating Companies (Mr. P. Torchio) and from the Electric Power Club (Messrs. James Burke and J. M. Smith).

Sub-committee No. 3, through Messrs. Schreiber and Del Mar, respectively, worked in collaboration with the Committees of the American Electric Railway Engineering Association, and the Association of Railway Electrical Engineers.

*Sub-committee No. 3 was a joint subcommittee of the Standards Committee and of the Railway Committee. The members opposite whose names occurs an asterisk, represented the latter committee.

The following members, although not appointed on the Standards Committee, have materially contributed to its work and have attended its meetings:

Carl J. Fechheimer, E. D. Priest, R. B. Williamson, K. A. Pauly, L. F. Blume, C. Renshaw, G. H. Hill, C. J. Hixson.

The radical revision begun in 1911 was completed by this Committee and approved by the Board of Directors at a special meeting held on July 10, 1914, subject to editorial revision by the Committee, and to go into force on Dec. 1, 1914.

The Committee of 1914-1915 which carried out the editorial revision, found it impossible to complete the work satisfactorily by Dec. 1st. The edition of July 1st, 1915, approved by the Board of Directors at its meeting of June 30, 1915, thus represents substantially the completion and clarification of the previous radical revision, although it includes a number of important additions. This Committee was constituted as follows:

A. E. KENNELLY, Chairman, Harvard University Cambridge, Mass.
C. A. ADAMS, Secretary, Harvard University, Cambridge, Mass.

JAMES BURKE, Erie, Pa.	W. H. POWELL, Milwaukee, Wis.
W. A. DEL MAR, New York,	CHARLES ROBBINS, East Pittsburgh, Pa.
H. W. FISHER, Perth Amboy, N. J.	L. T. ROBINSON, Schenectady, N. Y.
G. L. KNIGHT, Brooklyn, N. Y.	E. B. ROSA, Washington, D. C.
H. M. HOBART, Schenectady, N. Y.	C. E. SKINNER, East Pittsburgh, Pa.
F. B. JEWETT, New York.	J. M. SMITH, New York.
P. JUNKERSFELD, Chicago, Ill.	H. G. STOTT, New York.
W. L. MERRILL, Schenectady, N. Y.	P. H. THOMAS, New York.

NOTE.

The Standards Committee takes this occasion to draw the attention of the membership to the value of suggestions based upon experience gained in the application of the Rules to general practise.

Any suggestions looking toward improvement in the Rules should be communicated to the Secretary of the Institute, for the guidance of the Standards Committee in the preparation of future editions.

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PREFACE.

In framing these rules, the chief purpose has been to define the terms and conditions which characterize the rating and behavior of electrical apparatus, with special reference to the conditions of acceptance tests.

It has not been the purpose of the rules to standardize the dimensions or details of construction of any apparatus, lest the progress of design and production should be hampered.

DEFINITIONS

NOTE. The following definitions are intended to be practically descriptive, rather than scientifically rigid.

CURRENT, E.M.F. and POWER.

(The definitions of currents given below apply also, in most cases, to electromotive force, potential difference, magnetic flux, etc.)

1 **Direct Current.** A unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

2 **Pulsating Current.** A current which pulsates regularly in magnitude. As ordinarily employed, the term refers to unidirectional current.

3 **Continuous Current.** A practically non-pulsating direct current.

4 **Alternating Current.** A current which alternates regularly in direction. Unless distinctly otherwise specified, the term "alternating current" refers to a periodic current with successive half waves of the same shape and area.

5 **Oscillating Current.** A periodic current whose frequency is determined by the constants of the circuit or circuits.

6 **Cycle.** One complete set of positive and negative values of an alternating current.

7 **Electrical Degree.** The 360th part of a cycle.

8 **Period.** The time required for the current to pass through one cycle.

9 **Frequency.** The number of cycles or periods per second. The product of 2π by the frequency is called the *angular velocity* of the current.

10 **Root-Mean-Square** or **Effective Value.** The square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated r.m.s. Unless otherwise specified, the numerical value of an alternating current refers to its r.m.s. value. The r.m.s. value of a sinusoidal wave is equal to its maximum, or crest value, divided by $\sqrt{2}$. The word "virtual" is sometimes used in place of r.m.s., particularly in Great Britain.

11 **Wave-Form** or **Wave-Shape.** The shape of the curve obtained when the instantaneous values of an alternating current are plotted against time in rectangular co-ordinates. The distance along the time axis corresponding to one complete cycle of values is taken as 2π radians, or 360 degrees. Two alternating quantities are said to have the same wave-form when their ordinates of corresponding phase (see **§ 13**) bear a constant ratio to each other. The wave-shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is represented.

12 **Simple Alternating** or **Sinusoidal Current**. One whose wave-shape is sinusoidal.

Alternating-current calculations are commonly based upon the assumption of sinusoidal currents and voltages.

13 **Phase.** The distance, usually in angular measure, of the base of any ordinate of an alternating wave from any chosen point on the time axis, is called the phase of this ordinate with respect to this point. In the case of a sinusoidal alternating quantity, the phase at any instant may be represented by the corresponding position of a line or *vector* revolving about a point with such an angular velocity ($\omega = 2\pi f$), that its projection at each instant upon a convenient reference line is proportional to the value of the quantity at that instant.

14 **Non-Sinusoidal Quantities.** Quantities that cannot be represented by vectors of constant length in a plane. The following definitions of phase, active component, reactive component, etc., are not in general applicable thereto. Certain "equivalent" values, as defined below, may, however, be used in many instances, for the purpose of approximate representation and calculation.

15 **Crest-Factor or Peak-Factor.** The ratio of the crest or maximum value to the r.m.s. value. The crest factor of a sine-wave is $\sqrt{2}$.

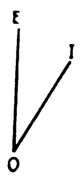
16 **Form Factor.** The ratio of the r.m.s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine-wave is 1.11.

17 **The Distortion Factor of a wave.** The ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

18 **Equivalent Sine Wave.** A sine wave which has the same frequency and the same r.m.s. value as the actual wave.

*19 **Phase Difference: Lead and Lag.** When corresponding cyclic values of two sinusoidal alternating quantities of the same frequency occur at different instants, the two quantities are said to differ in phase by the angle between their nearest corresponding values; *e.g.*, the phase angle between their nearest ascending zeros or between their nearest positive maxima. That quantity whose maximum value occurs first in time is said to lead the other, and the latter is said to lag behind the former.

*20 **Counter-Clockwise Convention.** It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector, † as in the accompanying diagram, where OI represents the vector of a current in a simple alternating-current circuit, lagging behind the vector OE of impressed e.m.f.



*21 **The Active or In-Phase Component** of the current in a circuit is that component which is in phase with the voltage across the circuit; similarly the active component of the voltage across a circuit is that component which is in phase with the current. The use of the term *energy component* for this quantity is disapproved.

*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

†See Publication 12 of the International Electrotechnical Commission (Report of Turin Meeting, Sept. 1911, p. 78).

***22 Reactive or Quadrature Component of the current in a circuit.** That component which is in quadrature with the voltage across the circuit; similarly, the reactive component of the voltage across the circuit is that component which is in quadrature with the current. The use of the term *wattless component* for this quantity is disapproved.

***23 Reactive Factor.** The sine of the angular phase difference between voltage and current; *i. e.*, the ratio of the reactive current or voltage to the total current or voltage.

***24 Reactive Volt-Amperes.** The product of the reactive component of the voltage by the total current, or of the reactive component of the current by the total voltage.

***25 Non-Inductive Load and Inductive Load.** A *non-inductive* load is a load in which the current is in phase with the voltage across the load. An *inductive* load is a load in which the current lags behind the voltage across the load. A *condensive* or *anti-inductive* load is one in which the current leads the voltage across the load.

26 Power in an Alternating-Current Circuit. The average value of the products of the coincident instantaneous values of the current and voltage for a complete cycle, as indicated by a wattmeter.

27 Volt-Amperes or Apparent Power. The product of the r.m.s. value of the voltage across a circuit by the r.m.s. value of the current in the circuit. This is ordinarily expressed in kv-a.

28 Power Factor. The ratio of the power (cyclic average as defined in **§26**) to the volt-amperes. In the case of sinusoidal current and voltage, the power factor is equal to the cosine of their difference in phase.

29 Equivalent Phase Difference. When the current and e.m.f. in a given circuit are non-sinusoidal, it is customary, for purposes of calculation, to take as the "equivalent" phase difference, the angle whose cosine is the power factor (see **§28**) of the circuit. There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave, or in both, may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e.g.*, the case of an a-c. arc. In such cases, the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

30 Single-Phase. A term characterizing a circuit energized by a single alternating e.m.f. Such a circuit is usually supplied through two wires. The currents in these two wires, counted positively outwards from the source, differ in phase by 180 degrees or a half-cycle.

31 Three-Phase. A term characterizing the combination of three circuits energized by alternating e.m.f.'s. which differ in phase by one-third of a cycle; *i.e.*, 120 degrees.

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*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

32 **Quarter-Phase, also called Two-Phase.** A term characterizing the combination of two circuits energized by alternating e.m.f's. which differ in phase by a quarter of a cycle; *i.e.*, 90 degrees.

33 **Six-Phase.** A term characterizing the combination of six circuits energized by alternating e.m.f's. which differ in phase by one sixth of a cycle; *i.e.*, 60 degrees.

34 **Polyphase.** A general term applied to any system of more than a single phase. This term is ordinarily applied to symmetrical systems.

Per Cent Drop.

50 In electrical machinery, the ratio of the **internal resistance drop** to the terminal voltage, expressed in per cent, is called the "*per cent resistance drop.*"

51 Similarly the ratio of the **internal reactance drop** to the terminal voltage, expressed in per cent, is called the "*per cent reactance drop.*"

52 Similarly the ratio of the **internal impedance drop** to the terminal voltage, expressed in per cent, is called the "*per cent impedance drop.*"

Unless otherwise specified, these per cent drops shall be referred to rated load and rated power factor.

53 **In the case of transformers,** the per cent drop will be the sum of the primary drop (reduced to secondary turns) and the secondary drop, in per cent of secondary terminal voltage.

54 **In the case of induction motors,** it is advantageous to express the drops in per cent of the internally induced e.m.f.

55 **The Load Factor of a machine, plant or system.** The ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain period of time, such as a day, a month, or a year, and the maximum is taken as the average over a short interval of the maximum load within that period.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load-factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

56 **Plant Factor.** The ratio of the average load to the rated capacity of the power plant, *i.e.*, to the aggregate ratings of the generators.

57 **The Demand of an installation or system.** The load which it puts on the source of supply, as measured at the receiving terminals. The demand may be as specified, contracted for, or used. It may be expressed either in kilowatts, kilovolt-amperes, amperes or other suitable units.

58 **The Maximum Demand of an installation or system.** Its greatest demand, as measured not instantaneously but averaged over a suitable and specified interval, such as a "five-minute maximum demand."

59 **Demand Factor.** The ratio of the maximum demand of any system or part of a system, to the total connected load of the system, or of the part of system, under consideration.

60 **Diversity Factor.** The ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

61 **Connected Load.** The combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system or part of the system under consideration.

62 **The Saturation Factor of a machine.** The ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

63 **The Percentage Saturation** of a machine at any excitation may be found from its saturation curve of generated voltage as ordinates, against excitation as abscissas, by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percentage, is the percentage of saturation and is independent of the scales selected for excitation and voltage. This ratio, as a fraction, is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity; or, if f be the saturation factor and p the percentage of saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

64 **Magnetic Degree.** The 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One **mechanical degree** is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

65 **The Variation in Prime Movers** which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 degrees.

66 **The Variation in Alternators** or alternating-current circuits in general, is the maximum angular displacement, expressed in electrical degrees, (one cycle = 360 deg.) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover.

67 **Relations of Variations in Prime Mover and Alternator.** If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct-connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

68 **The Pulsation in Prime Movers, or in the alternator connected thereto.** The ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

80 **Capacity.** The two different senses in which this word is used sometimes lead to ambiguity. It is therefore recommended that whenever such ambiguity is likely to arise, the descriptive term ***power capacity*** or ***current capacity*** be used, when referring to the power or current which a device can safely carry, and that the term "***Capacitance***" be used when referring to the electrostatic capacity of a device.

81 **Resistor.** A device, heretofore commonly known as a resistance, used for the operation, protection, or control of a circuit or circuits. See **§ 740.**

82 **Reactor.** A coil, winding or conductor, heretofore commonly known as a reactance coil or choke coil, possessing inductance, the reactance of which is used for the operation, protection or control of a circuit or circuits. See also **§ 214** and **736.**

83 **Efficiency.** The efficiency of an electrical machine or apparatus is the ratio of its useful output to its total input.

TABLE I.

90 **Symbols and Abbreviations.**

Name of Quantity.	Symbol for the Quantity.	Unit.	Abbreviation for the Unit.
Electromotive force, abbreviated e.m.f.	E, e	volt	....
Potential difference, abbreviated p.d.	V, v or E, e	"	....
Voltage	E, e or V, v	"	....
Current	I, i	ampere	....
Quantity of electricity	Q, q	coulomb, ampere-hour	....
Power	P, p	watt	....
Electrostatic flux	Ψ	....	....
Electrostatic flux density	D	....	....
Electrostatic field intensity	F		
Magnetic flux	Φ, φ	maxwell*	....
Magnetic flux density	$B, \mathfrak{B}$	gauss*	....
Magnetic field intensity	$H, \mathcal{H}$	gilbert per centimeter or gauss†	gilbert per cm. ....
Magnetomotive force, abbreviated m.m.f.	$\mathfrak{F}$	gilbert*	....
Intensity of magnetization.	J	....	....
Susceptibility	$\kappa = J/H$	....	....
Permeability	$\mu = B/H$	....	....

* An additional unit for m m. f. is the "ampere-turn", for flux the "line", for magnetic flux-density "maxwells per sq. in."

† The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric.

Resistance	R, r	ohm	....
Reactance	X, x	"	....
Impedance	Z, z	"	....
Conductance	g	mho	....
Susceptance	b	"	....
Admittance	Y, y	"	....
Resistivity	ρ	* ohm-centimeter	ohm-cm
Conductivity	γ	*mho per centimeter	mho per cm.
Dielectric constant	ϵ or k	....	....
Reluctance	$\mathcal{R}$	....	....
Capacitance (Electrostatic capacity)	C	farad	....
Inductance (or coefficient of self induction)	L	henry	....
Mutual Inductance (or coefficient of mutual induction)	M	henry	....
Phase displacement	θ, φ	degree or radian	•
Frequency	f	cycle per second	~
Angular velocity	ω	radian per second	....
Velocity of rotation	n	revolution per second	rev. per sec.
Number of conductors or turns	N	convolution or turns of wire	
Temperature	T, t, θ	degree centigrade	°C
Energy, in general	U or W	joule, watt-hour	....
Mechanical work	W or A	joule, watt-hour	....
Efficiency	η	per cent	....
Length	l	centimeter	cm.
Mass	m	gram	g.
Time	t	second	sec.
Acceleration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665†	g_0	centimeter per second per second	cm. per sec. per sec.

*Note. The numerical values of these quantities are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube, as commonly stated.

†This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45° Latitude and sea level. Later researches, however, have shown that the most reliable value for 45° and sea-level is slightly different; but this does not affect the standard value given above.

91 E_m, I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r.m.s. values (see §10) and P for the average value of the power, or the active power. These distinctions are not necessary in dealing with continuous-current circuits. In print, vector quantities should be represented by bold-face capitals.

CLASSIFICATION OF MACHINERY.

100 The machinery under consideration in these rules may be classified in various ways, these various classifications overlapping or interlocking in considerable degree. Briefly, they are Direct-Current or Alternating-Current, Rotating or Stationary. Under Rotating Apparatus there are two principal classifications: *First*, according to the function of the machines; Motors, Generators, Boosters, Motor-Generators, Dynamotors, Double-Current Generators, Converters and Phase Modifiers; *Second*, according to the type of construction or principle of operation; Commutating, Synchronous, Induction, Unipolar, Rectifying. Obviously, some of these machines could be rationally included in either classification, *e.g.*, Motor-Generators and Rectifying Machines.

In the following, self-evident definitions have for the most part, been omitted.

ROTATING MACHINES.

FUNCTIONAL CLASSIFICATION OF ROTATING MACHINES.

101 **Generator.** A machine which transforms mechanical power into electrical power.

102 **Motor.** A machine which transforms electrical power into mechanical power.

103 **Booster.** A generator inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

104 **Motor-Generator Set.** A transforming device consisting of a motor mechanically coupled to one or more generators.

105 **Dynamotor.** A transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

106 A **Direct-Current Compensator** or **Balancer** comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

107 A **Double-Current Generator** supplies both direct and alternating currents from the same armature-winding.

108 A **Converter** is a machine employing mechanical rotation in changing electrical energy from one form into another. There are several types of converters as follow:

109 **A Direct-Current Converter** converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor-generator set or a dynamotor.

110 **A Synchronous Converter** (sometimes called a Rotary Converter) converts from an alternating to a direct current, or vice-versa. It is a synchronous machine with a single closed-coil armature winding, a commutator and slip rings.

111 **A Cascade Converter,** also called a **Motor Converter,** is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i.e.*, it is a synchronous converter concatenated with an induction motor.

112 **A Frequency Converter** converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

113 **A Rotary Phase-Converter** converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

114 **A Phase-Modifier,** also called *a Phase-Advancer*, is a machine which supplies reactive volt-amperes; *e.g.* to an induction motor, or to the system to which it is connected. Phase modifiers may be either synchronous or asynchronous.

115 **A Synchronous Phase-Modifier,** sometimes called a Synchronous Condenser, is a synchronous motor, running either idle or with load, the field excitation of which may be varied so as to modify the power-factor of the system, or through such modification to influence the load voltage. The function of a Synchronous Phase-Modifier is to supply reactive volt-amperes to the system with which it is connected.

CONSTRUCTIONAL CLASSIFICATION OF ROTATING MACHINES

Commutating Machines

130 **Direct-Current Commutating Machines** comprise a magnetic field of constant polarity, an armature, and a commutator connected therewith. These include: Direct-Current Generators; Direct-Current Motors; Direct-Current Boosters; Direct-Current Motor-Generator Sets and Dynamotors; Direct-Current Compensators or Balancers; and Arc Machines.

131 **Alternating-Current Commutating Machines*** comprise a magnetic field of alternating polarity, an armature, and commutator connected therewith.

*Definitions of a-c. commutator-motors have not yet been agreed upon. The differences of opinion are fundamental and relate to the whole system to be employed in naming the numerous types. One example of this difference is in connection with the definition of the term " Repulsion-Motor", some desiring to extend its use to cover all a.c. commutator motors with short-circuited brushes, and others to substitute more systematic names for the various species of short-circuited brush motors.

132 **Synchronous Commutating Machines** include synchronous converters, cascade-converters, and double-current generators.

133 **Synchronous Machines** Comprise a constant magnetic field and an armature receiving or delivering alternating-currents in synchronism with the motion of the machine; *i.e.*, having a frequency strictly proportional to the speed of the machine. They may be sub-divided as follow:

134 **An Alternator** is a synchronous alternating-current generator, either single-phase or polyphase.

135 **A Polyphase Alternator** is a polyphase synchronous alternating-current generator, as distinguished from **a singlephase alternator.**

136 **An Inductor Alternator is an Alternator** in which both field and armature windings are stationary, and in which masses of iron or inductors, by moving past the coils, alter the magnetic flux through them. It may be either singlephase or polyphase.

137 **A Synchronous Motor** is a machine structurally identical with an alternator, but operated as a motor.

138 **Induction Machines** include apparatus wherein primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, certain types of frequency converters and certain types of rotary phase-converters.

139 **An Induction Motor** is an alternating-current motor, either singlephase or polyphase, comprising independent primary and secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

140 **An Induction Generator** is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

141 **Unipolar or Acyclic Machines** are direct-current machines, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

SPEED CLASSIFICATION OF MOTORS.

150 **Motors** may, for convenience, be classified with reference to their speed characteristics as follow:

151 **Constant-Speed Motors,** whose speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

152 **Multispeed Motors** two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load; such as motors with two armature windings, or induction motors in which the number of poles is changed by external means.

153 **Adjustable-Speed Motors,** in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load, such as shunt motors designed for a considerable range of speed variation.

154 **Varying-Speed Motors,** or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound-wound motors, and series-shunt motors. As a sub-class of varying-speed motors, may be cited, **adjustable varying-speed motors,** or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; such as compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

CLASSIFICATION OF ROTATING MACHINES RELATIVE TO THE DEGREE OF ENCLOSURE OR PROTECTION

160 The following types are recognized:

Open
Protected
Semi-enclosed
Enclosed
Separately ventilated
Water-cooled
Self-ventilated
Drip-proof
Moisture-resisting
Submersible
Explosion-proof
Explosion-proof slip-ring enclosure

161 An **"open" machine** is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

162 A **"protected" machine** is one in which the armature, field coils, and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

163 A **"semi-enclosed" machine** is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding ½ of a square inch (3.2 sq. cm.) in area.

164 An **"enclosed" machine** is so completely enclosed by integral or auxiliary covers as to prevent a circulation of air between the inside and outside of its case, but not sufficiently to be termed air-tight.

165 A **"separately ventilated" machine** has its ventilating air supplied by an independent fan or blower external to the machine.

166 A **"water-cooled" machine** is one which mainly depends on wate circulation for the removal of its heat.

167 A "**self-ventilated**" **machine** differs from a separately ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a pipe attached to the machine, this should be so stated.

168 A "**drip-proof**" **machine** is one so protected as to exclude falling moisture or dirt. A "drip proof" machine may be either "open" or "semi-enclosed", if it is provided with suitable protection integral with the machine, or so enclosed as to exclude effectively falling solid or liquid material.

169 A **moisture-resisting machine** is one in which all parts are treated with moisture-resisting material. Such a machine shall be capable of operating continuously or intermittently in a very humid atmosphere, such as in mines, evaporating rooms, etc.

170 A "**submersible**" **machine** is a machine capable of withstanding complete submersion, in fresh water or sea water, as may be specified, for four hours without injury.

171 An "**explosion-proof**" **machine** is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

172 An induction motor in which the slip rings and brushes alone are included within an explosion-proof case should not be described as an explosion-proof machine, but as a machine "**with explosion-proof slip-ring enclosure.**"

STATIONARY INDUCTION APPARATUS

200 **Stationary Induction Apparatus** changes electric energy to electric energy, through the medium of magnetic energy, without mechanical motion. It comprises several forms, distinguished as follow:

201 **Transformers**, in which the primary and secondary windings are ordinarily insulated one from another.

202 The terms "**high-voltage**" and "**low-voltage**" are used to distinguish the winding having the greater from that having the lesser number of turns. The terms "**primary**" and "**secondary**" serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary.

203 The **rated current of a constant-potential transformer** is that secondary current which, multiplied by the rated-load secondary voltage, gives the kv-a. rated output. That is, a transformer of given kv-a. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated secondary voltage.

The **Rated Primary Voltage** of a constant-potential transformer is the rated secondary voltage multiplied by the turn ratio.

204 The **ratio of a transformer,** unless otherwise specified, shal be the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding; *i.e.*, the "turn-ratio."

205 The **voltage ratio** of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified conditions of load.

206 The "**current ratio**" of a current-transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified conditions of load.

207 The "**marked ratio**" of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage, frequency, load and power factor of the load.

208 **Volt-Ampere Ratio of Transformers.**

The volt-ampere ratio, which should not be confused with real efficiency, is the ratio of the volt-ampere output to the volt-ampere input of a transformer, at any given power factor.

209 **Auto-transformers** have a part of their turns common to both primary and secondary circuits.

210 **Voltage Regulators** have turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation or the phase relation between the circuit-voltages is variable at will. They are of the following three classes:

211 **Contact Voltage Regulators,** in which the number of turns in one or both of the coils is adjustable.

212 **Induction Voltage Regulators,** in which the relative positions of the primary and secondary coils are adjustable.

213 **Magneto Voltage Regulators,** in which the direction of the magnetic flux with respect to the coils is adjustable.

214 **Reactors,** heretofore commonly called **Reactance-Coils,** also called **Choke Coils**; a form of stationary induction apparatus used to supply reactance or to produce phase displacement. See also **§82** and **736**.

INSTRUMENTS

225 **An Ammeter** is an instrument for measuring current, indicating in amperes.

226 **A Voltmeter** is an instrument for measuring difference of potential, indicating in volts.

227 **A Crest Voltage Meter** is a voltmeter designed to indicate either the crest; *i.e.*, the maximum value, of an alternating voltage, or the r.m.s. value of the sinusoidal voltage having the same crest value.

288 **A Wattmeter** is an instrument for measuring electrical power, indicating in watts.

229 **Recording Ammeters, Voltmeters, Wattmeters, etc.,** are instruments which record graphically upon a time-chart the values of the quantities they measure.

230 **A Watt-hour Meter** is an instrument for registering watt-hours. This term is to be preferred to the term "integrating wattmeter."

231 **A Line-Drop Voltmeter Compensator** is a device used in connection with a voltmeter, which causes the latter to indicate the voltage at some distant point of the circuit.

232 **A Synchroscope, sometimes called a Synchronism Indicator,** is a device which, in addition to indicating synchronism, shows whether the incoming machine is fast or slow.

STANDARDS FOR ELECTRICAL MACHINERY

250 *The expressions " machinery " and " machines " are here employed in a general sense, in order to obviate the constant repetition of the words " machinery or induction apparatus."*

251 *All temperatures are to be understood as centigrade.*

252 *The expression " capacity " is to be understood as indicating " capability ", except where specifically qualified as, for instance, in the case of allusions to electrostatic capacity, i. e., capacitance.*

253 *Wherever special rules are given for any particular type of machinery or apparatus (such as switches, railway motors, railway substation machinery, etc., these special rules shall be followed, notwithstanding any apparent conflict with the provisions of the more general sections. In the absence of special rules on any particular point, the general rules on this point shall be followed.*

260 **Objects of Standardization.** To ensure satisfactory results, electrical machinery should be specified to conform to the Institute Standardization Rules, in order that it shall comply, in operation, with approved limitations in the following respects, so far as they are applicable.

Operating temperature
Mechanical strength
Commutation
Dielectric strength
Insulation resistance
Efficiency
Power factor
Wave shape
Regulation

261 **Capacity or Available Output of an Electrical Machine.** So far as relates to the purposes of these Standardization Rules, the Institute defines the Capacity of an Electrical Machine as the load which it is capable of carrying for a specified time (or continuously), without exceeding in any respect the limitations herein set forth.

Except where otherwise specified, the capacity of an electrical machine shall be expressed in terms of its available *output.* For exceptions see **§277** and **802.**

262 **Rating of an Electrical Machine.** Capacity should be distinguished from Rating. The Rating of a machine is the output marked on the Rating Plate, and shall be based on, but shall not exceed, the maximum* load which can be taken from the machine under prescribed conditions of test. This is also called the rated output.

*The term " maximum load " does not refer to loads applied solely for mechanical, commutation, or similar tests.

263 **The Principle upon which Machine Ratings** are based, so far as relates to thermal characteristics, is that the rated load, applied continuously or for a stated period, shall produce a temperature rise which, superimposed upon a standard ambient temperature, will not exceed the maximum safe operating temperature of the insulation.

264 **A. I. E. E. and I. E. C. Ratings**. When the prescribed conditions of test are those of the A. I. E. E. Standardization Rules, the rating of the machine is the Institute Rating. (See **§620**). When the prescribed conditions of the test are those of the I. E. C.† Rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate.

265 **Standard Temperature and Barometric Pressure for Institute Rating.** The Institute Rating of a machine shall be its capacity when operating with a cooling medium of the ambient temperature of reference (40° for air or 25° for water, see **§305** and **309**) and with barometric conditions within the range given in **§308.** See **§320.**

266 **The Temperatures Rises Specified in these Rules** apply to all ambient temperatures up to and including 40°C.

267 **Any Machinery Destined for Use with Higher Ambient** temperatures or cooling mediums, and also any machinery for operation at altitudes for which no provision is made in **§308,** should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these Rules will, however, afford guidance in such cases.

UNITS IN WHICH RATING SHALL BE EXPRESSED

274 The rating of **Direct-Current Generators,** shall be expressed in kilowatts (kw.) available at the terminals.

275 The rating of **Alternators** and **Transformers,** shall be expressed in kilovolt-amperes (kv-a.) available at the terminals, at a specified power factor. The corresponding kilowatts should also preferably be stated.

276 It is strongly recommended that the **rating of motors** shall be expressed in kilowatts* (kw.) available at the shaft. (An ex-

†I. E. C. stands for "International Electrotechnical Commission." This rating has not yet been established.

*Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practice of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

kw.————approx. equiv. h.p.————

The horse power rating of a motor may for practical purposes, be taken as 4/3 of the kilowatt rating.

In order to lay stress upon the preferred future basis, it is desirable that on Rating Plates, the Rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.

ception to this rule is made in the case of Railway motors, which, for some purposes, are also rated by their *input*, see **§802.**)

277 **Auxiliary machinery,** such as regulators, resistors, reactors, balancer sets, stationary and synchronous condensers, etc., shall have their ratings appropriately expressed. It is essential to specify also the voltage (and frequency, if a-c.,), of the circuits on which the machinery may appropriately be used.

KINDS OF RATING

There are various kinds of rating such as:

281 **Continuous Rating.** A machine rated for continuous service; shall be able to operate continuously at its rated output, without exceeding any of the limitations referred to in **§260.**

282 **Short-Time Rating.** A machine rated for short-time service; (*i.e.* service including runs alternating with stoppages of sufficient duration to ensure substantial cooling), shall be able to operate at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations referred to in **§260.** Such a rating is a **short-time rating.**

283 **Nominal Ratings.** For railway motors, and sometimes for railway-substation machinery, certain nominal ratings are employed. See **800** and **§765.**

284 **Duty-Cycle Operation.** Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load, may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty cycle.

285 **Standard durations of equivalent tests** shall be for machines operating under specified duty-cycles as follow:

5 minutes
10 "
30 "
60 "
120 "
and continuous.

Of these the first five are short-time ratings, selected as being thermally equivalent to the specified duty cycle.

When, for example, a short-time rating of 10 minutes duration is adopted, and the thermally equivalent load is 25 kw. for that period, then such a machine shall be stated to have a 10-minute rating of 25 kw.

286 In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are **within 5°C of the ambient temperature** at the time of starting the test.

287 In the absence of any specification as to the kind of rating, the continuous rating shall be understood.*

***An exception is made in the case of motors for railway service, where in the absence of of any specification as to the kind of rating, the " nominal rating " as defined in §819 and 415 shall be understood.**

288 Machines marked in accordance with **§264** shall be understood to have a continuous rating, unless otherwise marked in accordance with **§285**.

HEATING AND TEMPERATURE

300 **Temperature Limitations of the Capacity of Electrical Machinery.** The capacity, so far as relates to temperature, is usually limited by the maximum temperature at which the materials in the machine, especially those employed for insulation, may be operated for long periods without deterioration. When the safe limits are exceeded, deterioration is rapid. The insulating material becomes permanently damaged by excessive temperature, the damage increasing with the length of time that the excessive temperature is maintained, and with the amount of excess temperature, until finally the insulation breaks down.

301 The result of operating at temperatures in excess of the safe limit is to shorten the life of the insulating material. This shortening of life is, in certain special cases, warranted, when necessary for obtaining some other desirable result, as, for example, in some instances of railway and other motors for propelling vehicles, in providing greater power within a limited space. See **§804. Further instances** may also be noted in the cases of contactors, **controllers,** induction-starters, arc-lamp-magnet windings, etc., designed and constructed for operation at relatively high temperatures.

302 There does not appear to be any advantage in operating at lower temperatures than the safe limits, so far as the life of the insulation is concerned. Insulation may break down from various causes, and when these breakdowns occur, it is not usually due to the temperature at which the insulation has been operated, provided the safe limits have not been exceeded.

303 **The Ambient Temperature** is the temperature of the fluid or fluids which, coming into contact with the heated parts of a machine, carries off its heat convectively.

304 **The cooling fluid may** either be led to the machine through ducts, or through pipes, or merely surround the machine freely. In the former case the ambient temperature is to be measured at the intake of the machine itself. In the latter case see **§314.**

305 **Ambient Temperature of Reference for Air.** The standard ambient temperature of reference, when the cooling medium is **air,** shall be 40°C.

306 The permissible rises in temperature given in column 2 of table III in **§376** have been calculated on the basis of the standard ambient temperature of reference, by subtracting 40° from the highest temperatures permissible, which are given in column 1 of the same table.

307 A machine may be tested at any convenient ambient temperature, but whatever be the value of this ambient temperature, **the**

permissible rises of temperature must not exceed those given in column 2 of the table in **§376.**

308 **Altitude.** Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet.) For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See **§267.** It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent for each 100 meters (330 ft.) by which the altitude exceeds 1000 meters. Water cooled oil transformers are exempt from this reduction.

309 **Ambient Temperature of Reference for Water-Cooled Machinery.** For water-cooled machinery, the standard temperature of reference for incoming cooling water shall be 25° C, measured at the intake of the machine.

310 **In the testing of water-cooled transformers,** it is not necessary to take into account the surrounding air temperature, except where the cooling effect of the air is 15 per cent or more of the total cooling effect, referred to the standard ambient temperature of reference of 25°C. for water and 40°C. for air. When the effect of the cooling air is 15 per cent. or more of the total, the temperature of the cooling water should be maintained within 5°C. of the surrounding air. Where this is impractical, the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

311 **In the case of rotating machines,** cooled by forced draught, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts (see **§304**), and a weight of one to the surrounding room air. **In the case of air-cooled transformers,** see " exception " **§321.**

312 **Machines Cooled by Other Means.** For machines cooled by other means, special rules are necessary.

313 **Outdoor Machinery Exposed to Sun's Rays.**
Outdoor machinery not protected from the sun's rays at times of heavy load, must receive special consideration.

314 **Measurement of the Ambient Temperature During Tests of Machinery.**
The ambient temperature is to be measured by means of several thermometers placed at different points around and half-way up the machine, at a distance of 1 to 2 meters (3 to 6 feet), and protected from drafts, and abnormal heat radiation, preferably as in **§316.**

315 The value to be adopted for the ambient temperature during a test, is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

316 In order to avoid **errors due to the time lag** between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup. This can be made to respond to various rates of change, by proportioning the amount of oil to the metal in the containing cup. A convenient form for such an oil-cup consists of a massive metal cylinder, with a hole drilled partly through it. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The larger the machine under test, the larger should be the metal cylinder employed as an oil-cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a metal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in. high).

317 **Thermometers used for taking temperatures of Machinery** shall be covered by felt pads 3 mm. (⅛ inch) thick and 4 x 5 cm. wide (1½″x 2″), cemented on; oil putty may be used for stationary and small apparatus.

318 **In Transformer Testing,** and sometimes in testing other machines, it may be desirable to avoid errors due to time lag in temperature changes, by employing an idle unit of the same size and subjected to the same conditions of cooling as the unit under test, for obtaining the ambient temperature as described in **§310**.

319 Where **machines are partly below the floor line** in pits, the temperature of the rotor shall be referred to a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the rotor in and above the pit. Parts of the stator constantly in the pit shall be referred to the ambient temperature in the pit.

320 **Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference.** Numerous experiments have shown that deviation of the temperature of the cooling medium from that of the standard of reference, at the time of the heat run, has a negligible effect upon the temperature rise of the apparatus; therefore, no correction shall be applied for this deviation. It is, however, desirable that tests should be conducted at ambient temperatures not lower than 20°C.

321 *Exception*—**A Correction shall be applied** to the observed temperature rise of the windings of *Air-blast transformers*, due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction

shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i. e.* the ratio $274.5/(234.5 + t)$; where t is the ingoing cooling-air temperature.

Thus, a cooling-air room temperature of 30°C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40°C. (274.5° inferred absolute temperature) would be $274.5 \ / \ 264.5 \ = \ 1.04$, making the correction factor 1.04; so that an observed temperature rise of say 50°C. at the testing ambient temperature of 30°C. would be corrected to $50 \times 1.04 = 52$°C. this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40°C.

322 **Duration of Temperature Test of Machine for Continuous Service.** The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, if the test were prolonged until a steady final temperature was reached.

323 **Duration of Temperature Test of Machine with a Short-Time Rating.** The duration of the temperature test of a machine with a short-time rating shall be the time required by the rating. (See **§285** and **286**).

324 **Duration of Temperature Test for Machine having more than One Rating.** The duration of the temperature test for a machine with more than one rating shall be the time required by that rating which produces the greatest temperature rise. In cases where this cannot be determined beforehand, the machine shall be tested separately under each rating.

325 **Temperature Measurements during Heat Run.** Temperature measurements, when possible, shall be taken during operation, as well as when the machine is stopped. The highest figures thus obtained shall be adopted. In order to abridge the long heating period, in the case of large machines, reasonable overloads of current, during the preliminary period, are suggested for them.

TEMPERATURE MEASUREMENTS

340 **The Actual Temperatures attained** in the different parts of a machine, and not the rises in temperature, affect the life of the insulation of the machine. (See **§300** to **302**).

341 **The Temperatures in the Different Parts of a Machine** which it would be desirable to ascertain, are the maximum temperatures reached in those parts.

342 **Whatever may be the Ambient Temperature** when the machine is in service, the limits of the maximum observable temperature and of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of

temperature; such as commutation, stalling load and mechanical strength.

343 **As it is Usually Impossible to Determine the Maximum Temperature** attained in insulated windings, it is convenient to apply a correction to the observable temperature, so as to approximate the difference between the actual maximum temperature and the observable temperature by the method used. This correction, or margin of security, is provided to cover the errors due to fallibility in the location of the measuring devices, as well as inherent inaccuracies in measurement and methods.

344 **In Determining the Temperature of Different Parts of a Machine** three methods as provided. The appropriate method for any particular case is set forth below.

345 **Method No 1. Thermometer Method.**

This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermocouples or resistance coils embedded in the machine as described under Method No. 3.

346 **When Method No. 1 is Used,** the hottest-spot temperature for windings shall be estimated by adding a hottest-spot correction of 15°C to the highest temperature observed, in order to allow for the practical impossibility of locating any of the thermometers at the hottest spot.

347 *Exception.* When the thermometers are applied directly to the surfaces of bare windings, such as an edgewise strip conductor, or a cast copper winding, a hottest-spot correction of 5°C, instead of 15°C, shall be made. For commutators, collector rings, bare metallic surfaces not forming part of a winding, or for oil in which apparatus is immersed, no correction is to be applied.

348 **Method No. 2. Resistance Method.**

This method consists in the measurement of the temperature of windings by their increase in resistance, corrected* to the instant of shut-down when necessary. In the application of this method, careful thermometer measurements must also be made, whenever practicable without disassembling the machine†, in order to increase the probability of revealing the highest observable temperature. Which-

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*Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and times as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied.

In cases where successive measurements show *increasing* temperatures after shut-down, the highest value shall be taken.

†As one of the few instances in which the thermometer check cannot be applied in Method No. 2, the rotor of a turbo-alternator may be cited.

ever measurement yields the higher temperature, that temperature shall be taken as the " highest observable" temperature and a hot-test-spot correction of 10°C added thereto.

349 **The Temperature Co-efficient of Copper** shall be deduced from the formula $1/(234.5 + t)$. Thus, at an initial temperature $t = 40°C.$, the temperature co-efficient of increase in resistance per degree centigrade rise, is $1/(274.5) = 0.00364$. The following table, deduced from the formula, is given for convenience of reference.

TABLE II.

Temperature Coefficients of Copper Resistance.

Temperature of the winding, in degrees C. at which the initial resistance is measured.	Increase in resistance of copper per °C., per ohm of initial resistance.
0	0.00 427
5	0.00 418
10	0.00 409
15	0.00 401
20	0.00 393
25	0.00 385
30	0.00 378
35	0.00 371
40	0.00 364

350 **In Coils of Low Resistance,** where the joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used.

351 **The Temperature of the Windings of Transformers** is always to be ascertained by Method **2**. In the case of air-blast transformers, it is especially important to place thermometers on the coils near the air outlet.

352* **Method No. 3. Embedded Temperature-Detector Method.** This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When method No. 3 is used, it shall, when required, be checked by method No. 2; the hottest spot shall then be taken to be the highest value by either method, the required correction factors (**§348** and **§356**) being applied in each case.

353 **By Building into the Machine** suitably placed temperature detectors, a temperature not much less than that of the hottest spot will probably be disclosed. When these devices are adopted for such

temperature determinations, a liberal number shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur.

354 **Temperature-Detectors** should be placed in at least two sets of locations. One of these should be between a coil-side* and the core, and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge.

355 Method No. **3** should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) and over. It should also be applied to all machines of 5000 volts and over, if of over 500 kv-a., regardless of core width. This method is not required for induction-regulators, which shall be tested as transformers.

356 **Correction Factor for Method No. 3.**—In the case of two-layer windings, with detectors between coil-sides, and between coil-side and core, add 5° C to the highest reading. In single-layer windings, with detectors between coil-side and core and between coil-side and wedge, add to the highest reading 10° C. plus 1° C. per 1000 volts above 5000 volts of terminal pressure.

TEMPERATURE LIMITS

375 Table III gives the limits for the hottest-spot temperatures of insulations. The permissible limits are indicated in column 1 of the Table. The limits of temperature rise permitted under rated-load conditions are given in column 2, and are found by subtracting 40° C. from the figures in column 1. Whatever be the ambient temperature at the time of the test, the rise of temperature must never exceed the limits in column 2 of the table. The highest temperatures, and temperature rises, attained in any machine at the output for which it is rated, must not exceed the values indicated in the Table and clauses following.

376 **Permissible Temperatures and Temperature Rises For Insulating Materials.** Table III (see next page) gives the highest temperatures and temperature rises to which various classes of insulating materials may be subjected, based on a standard ambient temperature of reference of 40°C.

377 Note. The Institute recognizes the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150° C. and even higher. However, as sufficient data covering experience over a period of years at such temperatures is at present unavailable, the Institute adopts 125° C as a conservative limit for this class of insulation, and any increase above this figure shou'd be the subject of special guarantee by the manufacturer.

*A coil-side is one of the two active sides of a coil.

TABLE III.

Permissible Temperatures and Temperature Rises for Insulating Materials.

		1	2
Class	Description of Materia	Maximum Temperature to which the material may be subjected	Maximum Temperature Rise
A.	Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire*	105°C	65°C
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A. material or binder is used for structural purposes only, and may be destroyed without impairing the insulating or mechanical qualities of the insulation	125°C	85°C
C.	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc......	No limits specified.	

*For cotton, silk, paper and similar materials, when neither impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10°C below the limits fixed for Class A, in Table III.

378 When a lower-temperature class material is comprised in a completed product to such an extent, or in such ways, that its subjection to the temperature limits allowed for the higher-temperature class material, with which it is associated, would affect the integrity of the insulation either mechanically or electrically, the permissible temperature shall be fixed at such a value as shall afford ample assurance that no part of the lower-temperature class material shall be subjected to temperatures higher than those approved by the Institute and set forth above.

379 **TABLE IV**

Permissible Hottest Spot Temperatures and Limiting Observable Temperature Rises in other than Water-Cooled Machineay

Method	Windings	Class	A†	B
		Permissible Hottest-Spot Temperature....	105°	125°
METHOD I Thermometer ONLY See §345 to 347		Hottest Spot Correction..................	15°	15°
		Limiting Observable Temperature.........	90°	110°
		Limiting Observable Temperature Rise above 40°C.........................	50°	70°
METHOD II Resistance See §348		Hottest Spot Correction..................	10°	10°
		Limiting Observable Temperature.........	95°	115°
		Limiting Observable Temperature Rise above 40°C......................	55°	75°
METHOD III Embedded Temperature Detectors See § 352 to §356	Double-Layer Windings. For all Voltages	Hottest Spot Correction.......	5°	5°
		Limiting Observable Temperature.................	100°	120°
		Limiting Observable Temperature Rise above 40°C...	60°	80°
	Single-Layer Windings. For 5000 volts or less	Hottest Spot Correction.......	10°	10°
		Limiting Observable Temperature.................	95°	115°
		Limiting Observable Temperature Rise above 40°C...	55°	75°
	Single-Layer Windings. For more than 5000 Volts	Hottest Spot Correction	$10° + (E-5)$*	$10° + (E-5)$
		Limiting Observable Temperature.................	$95° - (E-5)$	$115° - (E-5)$
		Limiting Observable Temperature Rise above 40°C...	$55° - (E-5)$	$75° - (E-5)$

†For cotton, silk, paper and similar materials, when neither impreganted nor immersed in oil, the highest temperatures and temperature rise shall be 10°C. below the limits fixed for class A.

*In these formulas, E represents the rated pressure between terminals in kilovolts. Thus for a three-phase machine with single-layer winding, and with 11 kilovolts between terminals, the hottest-spot correction to be added to the maximum observable temperature will be 16°C.

Special Cases of Temperature limits.

385 **Temperature of Oil.** The oil in which apparatus is permanently immersed shall in no part have a temperature, observable by thermometer, in excess of 90°C.

386 **Water-Cooled Transformers.** In these the hottest-spot temperature shall not exceed 90°C.

387 **Railway Motor Temperature Limits,** see **§804** and **805.**

388 **Squirrel-Cage and Amortisseur Windings.** In many cases the insulation of such windings is largely for the purpose of making the conductors fit tightly in their slots, and the slightest effective insulation is ample. In other cases, there is practically no insulating material on the windings. Consequently, the temperature rise may be of any value such as will not occasion mechanical injury to the machine.

389 **Collector Rings.** The temperature of collector rings shall not be permitted to exceed the "hottest-spot" values set forth in **§376** and **379** for the insulations employed either in the collector rings themselves, or in adjacent insulations whose life would be affected by the heat from the collector rings.

390 **Commutators.** The observable temperature shall in no case be permitted to exceed the values given in **§376** and **379** for the insulation employed, either in the commutator or in any insulation whose life would be affected by the heat of the commutator.

391 **Cores.** The temperature of those parts of the iron core in contact with insulating materials must not be such as to occasion in those insulating materials temperatures or temperature rises in excess of those set forth in **§376** and **379.**

392 **Other parts,** (such as brush-holders, brushes, bearings, pole-tips, cores, etc.) All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material, may be operated at such temperatures as shall not be injurious in any respect.

METHODS OF LOADING TRANSFORMERS FOR TEMPERATURE TESTS

393 Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time (See **§322** to **324**). The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load.

An approved method of making these tests is the **"loading-back"** method. The principal variations of this method are—

394 **With duplicate single-phase transformers.**

Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions, while the other may be operating under slightly abnormal conditions.

395 **With one three-phase transformer.**

One three-phase transformer may be tested in a manner similar to (a), provided the primary and secondary windings are each connected in delta for the test. Normal three-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

396 **With three single-phase transformers.**

Duplicate single-phase transformers may be tested in banks of three, in a manner similar to (b) by connecting both primary and secondary windings in delta, and applying normal three-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.

397 Note:— Among other methods that have a limited application and can be used only under special conditions may be mentioned—

(1) Applying dead load by means of some form of rheostat.

(2) Running alternately for certain short intervals of time on open circuit and then on short circuit, alternating in this way until the transformer reaches steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss, as in normal operation.

ADDITIONAL REQUIREMENTS

398 **Short-Circuit Stresses.**

The Institute recognizes the self-destructibility, both mechanical and thermal, of certain sizes and types of machines, when subjected to severe short-circuits, and recommends that ample protection be provided in such cases, external to the machine if necessary.

Over-Speeds.

399 **All Types of Rotating Machines** shall be so constructed that they will safely withstand an over-speed of 25 per cent, except in the case of steam turbines, which, when equipped with emergency governors, shall be constructed to withstand 20 per cent over-speed.

400 **In the case of Series Motors,** it is impracticable to specify percentage values for the guaranteed over-speed, on account of the varying service conditions.

401 **Water-wheel Generators** shall be constructed for the maximum runaway speed which can be attained by the combined unit.

Momentary Loads.

402 **Continuously Rated Machines** shall be required to carry momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation, (See §**281, 764** and **803.**) and commutating machinery shall commutate successfully under this condition. Successful commutation is such that neither brushes nor commutator are injured by the test. In the case of direct-connected generators, this clause is not to be interpreted as requiring the prime mover to drive the generator at this overload.

403 **Machines for duty-cycle operation** shall be rated according to their equivalent load, either on the short-time or continuous basis, but if intended for operation with widely fluctuating loads, shall commutate successfully under their specified operating conditions. See **§ 284, 285.**

404 **Stalling Torque of Motors**

Motors for continuous service shall, except when otherwise specified be required to develop a running torque at least 175 per cent of that corresponding to the running torque at their rated load, without stalling.

Obviously, duty-cycle machines must carry their peak loads without stalling.

WAVE FORM

405 The **Sine Wave** shall be considered as standard, except where deviation therefrom is inherent in the operation of the system of which the machine forms a part.

406 **The deviation of wave form** from the sinusoidal is determined by superposing upon the actual wave, (as determined by oscillograph), the equivalent sine wave of equal length, in such a manner as to give the least difference, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave. A maximum deviation of the wave from sinusoidal shape not exceeding 10 per cent is permissible, except when otherwise specified.

EFFICIENCY AND LOSSES

420 **Machine Efficiency** is the ratio of the power delivered by the machine to the power received by it.

421 **Plant Efficiency** is the ratio of the energy delivered from the plant to the energy received by it in the a specified period of time.*

422 Two efficiencies are recognized, conventional efficiency and directly-measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed.

423 **Conventional Efficiency** of machinery is the ratio of the output to the sum of the output and the losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practicably indeterminable, and must, in many cases, either be approximated by an approved method of test or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

424 **Efficiencies based upon Conventional Losses** shall be specifically stated to be conventional efficiencies.

425 **Directly-Measured Efficiency.** Input and output determinations of efficiency may be made directly, measuring the output by brake,

* **An exception should be noted in the case of the efficiency of storage batteries.**

or equivalent, where applicable. Within the limits of practical application, the circulating-power method, sometimes described as the Hopkinson or "loading-back" method, may be used.

426 **Values of the Indeterminate Losses** may also be obtained by brake or other direct test, and used in estimating actual efficiencies of similar machines, by the separate-loss method.

427 **Normal Conditions.** The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave-shape, speed, temperature, or such of them as may apply in each particular case.

428 **Measurement of Efficiency.** Electric power shall be measured at the terminals of the apparatus. In polyphase machines, sufficient measurements shall be made on all phases to avoid errors of unbalance.

429 **Point at Which Mechanical Power Shall be Measured.** Mechanical power delivered by machines, shall be measured at the pulley, gearing, or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. See, however, an exception in §800.

430 **The Efficiency of Alternating-Current machinery** shall be measured when the current is in phase with the terminal voltage, unless otherwise specified, or unless a definite phase difference is inherent in the apparatus, as in induction machinery.

431 **Efficiency of Alternating-Current Machinery in regard to WaveShape.** In determining the efficiency of alternating-current machinery, the sine wave is to be considered as standard, unless a different wave form is inherent in the operation of the system. See §405.

432 **Temperature of Reference for Efficiency Determinations.** The efficiency, at all loads, of all apparatus, shall be corrected to a reference temperature of 75°C.

433 **The losses in constant-potential machinery,** either of the stationary type, or of the constant-speed rotary type, are of two classes; namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also I^2R losses in any shunt windings. The latter include I^2R losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no load, deducting any series I^2R losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.

434 **Stray Load Losses.** The above simple method of determining the losses and hence the efficiency is only approximate, since the losses which are assumed to be constant do actually vary to some extent with the load, and also because the actual loss in the copper windings is sometimes appreciably greater than the calculated I^2R loss. The difference between the approximate losses, as above determined, and the actual losses, is termed the "stray load losses"*.

*In Table V, the stray load losses include f, h, i, k, l and m; but do not include increased core losses due to increased excitation for compensating internal drop under load.

These latter are due to distortions in electric or magnetic fluxes from their no-load distributions or values, brought about by the load current. They are usually only approximately measurable, or may be indeterminable.

TABLE V

Classification of Losses in Machinery

435 Losses in machinery may be classified as follows:

Accurately Measurable or Determinable	*Approximately Measurable or Determinable*	*Indeterminable*
a. No-Load Core Losses including eddy-current losses in conductors at no-load	*c*. Brush Friction Loss	*h*. Iron Loss due to flux distortion.
b. Load I^2R losses in windings No-Load I^2R " " "	*d*. Brush-Contact Loss	*i*. Eddy-Current losses in conductors due to transverse fluxes occasioned by the load currents.
	e. Losses due to windage and to bearing friction	*k*. Eddy-Current losses in conductors due to tooth saturation resulting from distortion of the main flux.
	f. Extra copper loss in transformer windings, due to stray fluxes caused by load currents	*l* Tooth-frequency losses due to flux distortion under load.
	g. Dielectric Losses.	*m*. Short-Circuit Loss of Commutation.

436 **Evaluation of Losses.** The larger individual losses are either accurately or approximately determinable, but certain of the indeterminable losses reach values in various kinds of machinery which require that they should be taken into account.

Methods of measuring, approximating or allowing for these various losses are given below.

LOSSES TO BE TAKEN INTO ACCOUNT IN VARIOUS TYPES OF MACHINES

440 **Direct-Current Commutating Motors and Generators.**

No-load core losses. (Accurately Measurable or Determinable).

I^2R loss in all windings. (Acc. Meas. or Deter.)

Brush contact I^2R loss. (Approximately Meas. or Deter). Unless otherwise specified, use the Institute Standard of 1 volt

for contact drop per brush; *i. e.*, 2 volts for total brush drop, for either carbon or graphite brushes. See **§454** and **819**.

Friction of bearings and windage. (Approx. Meas. or Deter.)

Rheostat losses, when present. (Acc. Meas. or Deter.)

Brush friction. (Approx. Meas. or Deter.)

All indeterminable load losses (including stray-load iron losses) which may be important, which vary with the design, and for which no satisfactory method of determination has been found, shall be included as zero per cent in estimating conventional efficiency.

441 **Synchronous Motors and Generators.**

No-load core losses. (Acc. Meas. or Deter.)

I^2R loss in all windings. (Acc. Meas. or Deter.) based upon rated kw. and power factor.

Stray load-losses. (Indeterminable.) In approximating these losses, the method described in **§458** shall be employed.

Friction of bearings and windage. (Approx. Meas. or Deter.)

Brush friction and brush-contact loss is negligible.

Rheostat losses, when present, corresponding to rated kw. and power factor. (Acc. Meas. or Deter.)

442 **Induction Machines.**

No-load core losses. (Acc. Meas. or Deter.)

I^2R losses in all windings. (Acc. Meas. or Deter.)

Stray load-losses. (Indeterminable.) In approximating these losses, the method described in **§459** shall be employed.

Brush friction when collector rings are present. (Approx. Meas. or Deter.)

Brush-contact loss. (Approximately Meas. or Deter.). Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454**.

Friction of bearings and windage (Approx. Meas. or Deter.)

443 **Commutating A-C. Machines**

No-load core losses. (Acc. Meas. or Deter.)

I^2R losses in all windings. (Acc. Meas. or Deter.)

Brush friction. (Approx. Meas. or Deter.)

Brush-contact loss. (Approx. Meas. or Deter.) Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454** and **819**.

Friction of bearings and windage. (Approx. Meas. or Deter.)

Short-Circuit loss of commutation. (Indeterminable.) Iron loss due to flux distortion. (Indeterminable.) Eddy-current losses due to fluxes varying with load and saturation. (Indeterminable.)	The Institute is not at this time prepared to make recommendations for approximating these losses.

444 **Synchronous Converters.**

No-load core losses. (Acc. Meas. or Deter.)

I^2R losses in all windings, based on rated **kw.** and power factor. (Approx. Meas. or Deter.) The I^2R losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using recognized factors.

Brush friction. (Approx. Meas. or Deter.)

Rheostat losses when present, corresponding to rated kw. and power factor. (Acc. Meas. or Deter.)

Brush-contact loss. (Approx. Meas. or Deter.) Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush,—for either carbon or graphite brushes. See **§454.**

Short-circuit loss of commutation. (Indeterminable) Iron loss due to flux distortion when present. (Indeterminable). Eddy-current losses due to fluxes varying with load and saturation. (Indeterminable.)	These losses, while usually of low magnitude, are erratic, and the Institute is not at this time prepared to make recommendations for approximating them.

Friction of bearings and windage. (Approx. Meas. or Deter.)

For the booster type of synchronous converter, where the booster forms an integral part of the unit, its losses shall be included in the total converter losses in estimating the efficiency.

445 **Transformers.**

No-load losses. These include the core loss and the I^2R loss due to the exciting current, (Acc. Meas. or Deter.) also the dielectric hysteresis loss in the insulation, (Approx. Meas. or Deter.) (See **§470.**)

I^2R losses in all windings. (Acc. Meas. or Deter.)

Stray load losses. (Approx. Meas. or Deter.). These include eddy-current losses in windings and core, due to fluxes varying with load. See **§471,** for the method of approximating these losses.

DETERMINATION OR APPROXIMATION OF LOSSES IN ROTATING MACHINERY

450 **Bearing Friction and Windage** may be determined as follows. Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have its brushes removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

The bearing friction and windage of induction motors may be measured by running motors free at the lowest voltage at which they will rotate continuously at approximately rated speed; the

watts input, minus I^2R loss, under these conditions being taken as the friction and windage.

In the case of engine-type generators, the windage and bearing friction loss is ordinarily very small,amounting to a fraction of one per cent of the output. In these rules this loss is neglected owing to its small value and the difficulty of measuring it.

451 **Brush Friction of Commutator and Collector Rings.** Follow the test of **§450,** taking an additional reading with the brushes in contact with the commutator or collector rings. The difference between the output obtained in the test in **§450** and this output shall be taken as the brush friction. Note: The surfaces of the commutator and brushes should already be smooth and glazed from running when this test is made.

452 **No-Load Core Loss.** Follow the test in **§451** with an additional reading taken with the machine excited. The difference between the output value of **§451** and the output value of this reading shall be taken as the no-load core loss. This no-load core loss shall be taken with the machine so excited, as to produce rated terminal voltage.

The Core Loss of Induction Motors may be determined by measuring the watts input to the motor when running free at normal rated voltage and frequency, and subtracting therefrom the no-load copper loss and the bearing friction and windage.

453 **No-Load Core Loss at the Internal Voltage Corresponding to Rated Load.** This shall be taken as in **§452,** except that the machine shall be so excited as to produce at the terminals the voltage corresponding to the calculated internal voltage for the load and power factor under consideration. For synchronous machines, since no generally accepted method is available for obtaining the stator reactance, the internal voltage shall be determined by correcting the terminal voltage for only the resistance drop.

454 **The Brush-Contact I^2R Loss** depends largely upon the material of which the brush is composed. As indicating the range of variation the following table will be of interest:

TABLE VI.

Brush-Contact Drop.

Grade of Brush	Volts drop across one brush-contact. (Average of positive and negative brushes)
Hard Carbon	1.1
Soft Carbon	0.9
Graphite	0.5 to 0.8
Metal-Graphite types	0.15 to 0.5 (The former for largest proportion of metal)

One volt drop per brush shall be considered as the Institute Standard drop corresponding to the I^2R brush-contact loss, for car-

bon and graphite brushes. Metal-graphite brushes shall be considered as special. See **§819**.

455 **Field-Rheostat Losses** shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

456 **Ventilating Blower.** When a blower is supplied as part of a machine set, the power required to drive it shall be charged against the complete unit; but not against the machine alone.

457 **Losses in Other Auxiliary Apparatus.** Auxiliary apparatus, such as a separate exciter for a generator or motor, shall have its losses charged against the plant of which the generator and exciter are a part, and not against the generator. An exception should be noted in the case of turbo-generator sets with direct-connected exciters, in which case the losses in the exciter shall be charged against the generator. The actual energy of excitation and the field-rheostat losses, if any, (see **§455**) shall be charged against the generator.

458 **Stray Load-Losses in Synchronous Generators and Motors.** These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load-losses are to be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the Institute is not yet prepared to specify a method for measuring them.

459 **Stray Load-Losses in Induction Machines.**

These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, and for a given stator current, measure the input the stator at different frequencies. Plot a curve of loss against frequency. At low frequencies, the loss becomes constant, indicating the I^2R value. The difference between this I^2R value and the total loss at normal frequency, shall be taken as the stray load-loss. This method is not accurate with induction motors in which the slots are entirely closed. In such machines these losses may be greater.

460 **Polyphase Induction-Motor Rotor I^2R Loss.** This should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{Output} \times \text{slip}}{1 - \text{slip}}$$

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor I^2R loss shall be determined by direct

resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{Rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to three-phase rotors. For rotors wound for two phase, use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 kw. or larger. The factor K usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

DETERMINATION OR APPROXIMATION OF LOSSES IN TRANSFORMERS

470 **No-Load Losses.** These shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated-load conditions. These no-load losses include core losses, consisting of hysteresis and eddy-current losses in the core, as well as dielectric loss in insulation due to electrostatic flux, which latter loss increases rapidly with temperature, and the test should therefore preferably be made at the reference temperature of 75°C.

471 **Stray Load-Losses.** These shall be measured by applying a primary voltage sufficient to produce rated-load current in the primary and secondary windings, the latter being short circuited. The stray load-losses will then be equal to the input decreased by the measured I^2R losses in both windings, as computed from resistance measurements at actual temperature, and the rated current. It is ordinarily immaterial whether the high-voltage or low-voltage winding is used as the primary winding in this test.

TESTS OF DIELECTRIC STRENGTH OF MACHINERY

480 **Basis for Determining Test Voltages.** The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machinery, and its normal operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended, have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

481 **Condition of Machinery to be Tested.** Commercial tests shall, in general, be made with the completely assembled machinery and not with individual parts. The machinery shall be in good condition, and high-voltage tests, unless otherwise specified, shall be applied before the machine is put into commercial service, and shall

not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests shall be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial testing. High-voltage tests to determine whether specifications are fulfilled, are admissible on new machines only. Unless otherwise agreed upon, high-voltage tests of a machine shall be understood as being made at the factory.

482 **Points of Application of Voltage.** The test voltage shall be successively applied between each electric circuit and all other electric circuits and metal parts grounded.

483 **Interconnected Polyphase Windings** are considered as one circuit. All windings of a machine except that under test, shall be connected to ground.

484 **Frequency, Wave Form and Test Voltage.** The frequency of the testing circuit shall not be less than the rated frequency of the apparatus tested. A sine-wave form is recommended. See **§405.** The test shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the specified test voltage. In d.c. machines, and in the general commercial application of a.c. machines, the testing frequency of 60 cycles per second is recommended.

485 **Duration of Application of Test Voltage.** The testing voltage for all classes of apparatus shall be applied continuously for a period of 60 seconds.

486 **Apparatus for Use on Single-Phase, 3-Phase-Delta or 3-Phase-Star Circuits.** Apparatus, such as transformers, which may be used in star connection on three-phase circuits, shall have the delta voltage of the circuits on which they may be used indicated on the rating plate and the test shall be based on such delta voltage.

VALUES OF A-C. TEST VOLTAGES

500 **The Standard Test for All Classes of Apparatus, Except as Otherwise Specified, Shall be Twice the Normal Voltage of the Circuit to Which the Apparatus is Connected, Plus 1000 Volts.**

501 *Exception*—**Alternating-Current Apparatus connected to Permanently Grounded Single-Phase Systems, for use on Permanently Grounded Circuits of more than 300 Volts,** shall be tested with 2.73 times the voltage of the circuit to ground + 1000 volts. **This does not refer to three-phase apparatus with grounded star neutral.**

502 *Exception*—**Distributing Transformers.** Transformers for primary pressures from 550 to 5000 volts, the secondaries of which are directly connected to consumers' circuits and commonly known as distributing transformers, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary windings shall be tested with twice their normal voltage plus 1000 volts.

503 *Exception*—**Auto-Transformers** used for starting purposes, shall be tested with the same voltage as the test voltage of the apparatus to which they are connected.

504 *Exception*—**Household Devices.** Apparatus taking not over 660 watts† and intended solely for operation on supply circuits not exceeding 250 volts, shall be tested with 900 volts, except in the case of heating devices which shall be tested with 500 volts at operating temperature.

505 *Exception*—**Apparatus for use on Circuits of 25 Volts or Lower,** such as bell-ringing apparatus,* electrical apparatus used in automobiles, apparatus used on low-voltage battery circuits, etc., shall be tested with 500 volts.

506 *Exception*—**Field Windings of Alternating-Current Generators** shall be tested with 10 times the exciter voltage, but in no case with less than 1500 volts nor more than 3500 volts.

507 *Exception*—Field Windings‡ of Synchronous Machines, including motors and converters which are to be started from alternating-current circuits, shall be tested as follows:

a. When machines are started with fields short-circuited they shall be tested as specified in §**506**.

b. When machines are started with fields open-circuited and sectionalized while starting, they shall be tested with 5000 volts.

c. When machines are started with fields open-circuited and connected all series while starting, they shall be tested with 5000 volts for less than 250-volt excitation and 8000 volts for excitation of 250 volts to 750 volts.

508 *Exception.* **Phase-Wound Rotors of Induction Motors.** The secondary windings of wound rotors of induction motors shall be tested with twice their normal induced voltage, plus 1000 volts.

When induction motors with phase-wound rotors are reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage, plus 1000 volts.

509 *Exception*—**Switches and Circuit Control Apparatus** above 600 volts, shall be tested with 2½ times rated voltage, plus 2000 volts. See §**720** to **741**.

510 *Exception*—**Assembled Apparatus.** Where a number of pieces of apparatus are assembled together and tested as an electrical unit, they shall be tested with 15 per cent lower voltage than the lowest required on any of the individual pieces of apparatus.

511 **Testing Transformers by Induced Voltage.** Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, in place of using a separate testing transformer. By "required voltage", is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

†The present National Electric Code power limit for a single outlet.

*This rule does not include bell-ringing transformers of ratio 125 to 6 volts. See National Electric Code

‡Series field coils should be regarded as part of the armature circuit and tested as such.

512 **Transformers with Graded Insulation** shall be so marked. They shall be tested by inducing the required test-voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. (See §**500**).

MEASUREMENT OF VOLTAGE IN DIELECTRIC TESTS OF MACHINERY

530 **Use of Voltmeters and Spark-Gaps in Insulation Tests.** When making insulation tests on electrical machinery. every precaution must be taken against the occurrence of any spark-gap discharges in the circuits from which the machinery is being tested. A non-inductive resistance of about one ohm per volt shall be inserted in series with one terminal of the spark gap. If the test is made with one electrode grounded, this resistance shall be inserted directly in series with the non-grounded electrode. If neither terminal is grounded, one-half shall be inserted directly in series with each electrode. In any case this resistance shall be as near the measuring gap as possible and not in series with the tested apparatus. The resistance will damp high-frequency oscillations at the time of breakdown and limit the current which will flow. A water tube is the most reliable form of resistor. Carbon resistors should not be used because their resistance may become very low at high voltages.

531 For Machinery of Low Capacitance. When the machinery under test does not require sufficient charging current to distort the high-voltage wave shape, or change the ratio of transformation, the spark gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark gap just breaks down. This adjustment should be made with the apparatus under test disconnected. The apparatus should then be connected, and with the spark gap about 20 per cent longer, the testing apparatus is again adjusted to give the voltage of the former breakdown, which is the assumed voltage of test. This voltage is to be maintained for the required interval.

532 For Machinery of High Capacitance. When the charging current of the machinery under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage should be made with the apparatus under test connected to the circuit and in parallel with the spark gap.

When making arc-over tests of large insulators, leads, etc. partial arc-over of the tested apparatus may produce oscillations which will cause the measuring gap to discharge prematurely. The measured voltage will then appear too high. In such tests the " equivalent " ratio " of the testing transformer should be measured by gap to within 20% of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. The measuring gap should then be greatly

lengthened out and the voltage increased until the tested apparatus arcs over. This arc-over voltage should then be determined by multplying the voltmeter reading by the equivalent ratio found above. Direct measurement of the spark-over voltage over one gap by another gap should always be avoided.

533 **Measurements with Voltmeter.** In measuring the voltage with a voltmeter, the instrument should preferably derive its voltage from the high-tension circuit, either directly, or by means of a voltmeter coil placed in the testing transformer, or through an auxiliary *ratio transformer*. It is permissible to measure the voltage at other places, such as the transformer primary provided corrections can be made for the variations in ratio caused by the charging current of the machinery under test, or provided there is no material variation of this ratio. In any case, when the capacitance of the apparatus to be tested is such as to cause wave distortion, the testing voltage must be checked by a spark gap as set forth in §**538**, or by a crest voltage meter. If the crest-voltage meter is calibrated in crest volts, its readings must be reduced to the corresponding r. m. s. sinusoidal value by dividing with $\sqrt{2}$.

534 **Measurements with Spark Gaps.** If proper precautions are observed, spark gaps may be used to advantage in checking the calibration of voltmeters when set up for the purposes of high-voltage tests of the insulation of machinery.

535 **Ranges of Voltages.** For the calibrating purposes set forth in §**534** the sphere-gap shall be used for voltages above 50 kv., and is to be preferred down to 30 kv. The needle spark-gap may, however, be used for voltages from 10 to 50 kv.

536 **The Needle Spark Gap.** The needle spark gap shall consist of new sewing needles, supported axially at the ends of linear conductors which are at least twice the length of the gap. There must be a clear space around the gap for a radius of at least twice the gap length.

537 The sparking distances in air between No. 00 sewing needle points for various root-mean-square sinusoidal voltages are as follows:

TABLE VII.

Needle-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometer)

R M S Kilovolts	Millimeters	R.M.S. Kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41		

The above values refer to a relative humidity of 80 per cent. Variations from this humidity may involve appreciable variations in the sparking distance.

538 **The Sphere Spark-Gap.** The standard sphere spark-gap shall consist of two suitably mounted metal spheres. When used as specified below, the accuracy obtainable should be approximately 2 per cent.

No extraneous body, or external part of the circuit, shall be nearer the gap than twice the diameter of the spheres. By the "gap" is meant the shortest path between the two spheres.

The shanks should not be greater in diameter than 1/5th the sphere diameter. Metal collars, etc., through which the shanks extend, should be as small as practicable and should not, during any measurement, come closer to the sphere than the maximum gap length used in that measurement.

The sphere diameter should not vary more than 0.1 per cent and the curvature, measured by a spherometer, should not vary more than 1 per cent from that of a true sphere of the required diameter.

539 **In using the spherometer** to measure the curvature, the distance between the points of contact of the spherometer feet should be within the following limits:

TABLE VIII

Spherometer Specifications

Diameter of Sphere in m.m.	Distance between contact points in mm.	
	Maximum	Minimum
62.5	35	25
125	45	35
250	65	45
500	100	65

539A **In using Sphere Gaps** constructed as above, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap; *e.g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

540 **The sparking distances between different spheres** for various r.m.s sinusoidal voltages shall be assumed to be as follows:

TABLE IX.
Sphere-Gap Spark-Over Voltages
(At 25°C and 760 mm. barometric pressure)

Kilo-volts	Sparking Distance in Millimeters.							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	..	..	..	..	..	..
20	8.6	8.6	..	..	..	..	..	..
30	13.5	13.5	14.1	14.1	..	..	..	..
40	19.2	19.2	19.1	19.1	..	..	..	..
50	25.5	25.0	24.4	24.4	..	..	..	..
60	34.5	32.0	30.	30.	29	29	..	..
70	46.0	39.5	36	36	35	35	..	..
80	62.0	49.0	42	42	41	41	41	41
90		60.5	49	49	46	45	46	45
100			56	55	52	51	52	51
120			79.7	71	64	63	63	62
140			108	88	78	77	74	73
160			150	110	92	90	85	83
180				138	109	106	97	95
200					128	123	108	106
220					150	141	120	117
240					177	160	133	130
260					210	180	148	144
280					250	203	163	158
300						231	177	171
320						265	194	187
340							214	204
360							234	221
380							255	239
400							276	257

The sphere gap is more sensitive than the needle gap to momentary rises of voltage and the voltage required to spark over the gap should be obtained by slowly closing the gap under constant voltage, or by slowly raising the voltage with a fixed setting of the gap. Open arcs should not be permitted in proximity to the gap during its operation, as they may affect its calibration.

AIR-DENSITY CORRECTION-FACTORS FOR SPHERE GAPS

541 **The Spark-Over Voltage,** for a given gap, decreases with decreasing barometric pressure and increasing temperature. This correction may be considerable at high altitudes.

The spacing at which it is necessary to set a gap to spark over at some required voltage, is found as follows: Divide tne required voltage by the correction factor given below in Table X. A new voltage is thus obtained. The spacing on the standard curves obtained from Table IX, corresponding to this new voltage, is the required spacing.

The voltage at which a given gap sparks over is found by taking the voltage corresponding to the spacing from the standard curves of Table IX, and multiplying by the correction factor.

When the variation from sea level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table X below, in which

$$\text{Relative air density} = \frac{0.392\,b}{273 + t}$$

b = barometric pressure in mm.

t = temperature in deg. C.

Corrected curves may be plotted for any given altitude, if desired.

Values of relative air density and corresponding values of the correction factor are tabulated below. It will be seen that for values above .9, the correction factor does not differ greatly from the relative air density.

TABLE X.

Air-Density Correction Factors for Sphere Gaps

Relative air density	Diameter of standard spheres in mm.			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

INSULATION RESISTANCE OF MACHINERY

550 **The insulation resistance of a machine** at its operating temperature shall be not less than that given by the following formula:

$$\text{Insulation Resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rated capacity in kv-a.} + 1000}$$

The formula only applies to dry apparatus. Such high values are not attainable in oil-immersed apparatus.

Insulation resistance tests shall, if possible, be made at a d.c. pressure of 500 volts. Since the insulation resistance varies with the pressure, it is necessary that, if a pressure other than 500 volts is to be employed in any case, this other pressure shall be clearly specified.

The order of magnitude of the values obtained by this rule is shown in the following table:

TABLE XI.

Insulation Resistance of Machinery

Rated Voltage of machine	Megohms		
	100 kv-a.	1000 kv-a.	10,000 kv-a.
100	0.091	0.05	—
1,000	0.91	0.50	0.091
10,000	9.1	5.0	0.91
100,000	—	50	9.1

551 It should be noted that the insulation resistance of machinery is of doubtful significance by comparison with the dielectric strength. The insulation resistance is subject to wide variation with temperature humidity and cleanliness of the parts. When the insulation resistance falls below that corresponding to the above rule, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying out the machine. The insulation-resistance test may therefore afford a useful indication as to whether the machine is in suitable condition for the application of the dielectric test.

REGULATION

DEFINITIONS

560 **Regulation.** The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be ex-

pressed by the "percentage regulation", which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at either one or the other load, taken as the normal value. It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75°C shall be considered as standard. If change of temperature should occur during the tests, the results shall be corrected to the reference temperature of 75°C.

The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a.c. generators.

It is usual to state the regulation of d-c. generators by giving the numerical values of the voltage at no load and rated load, and in some cases it is advisable to state regulation at intermediate loads.

561 The **Regulation of d-c. Generators** refers to changes in voltage corresponding to gradual changes in load and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

In determining the regulation of a compound-wound d-c. generator, two tests shall be made, one bringing the load down and the other bringing the load up, between no-load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

562 In **constant-potential a-c. generators,** the regulation is the rise in voltage (when the specified load at specified power factor is thrown off) expressed in per cent of normal rated-load voltage.

563 In **constant-current machines,** the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

564 In **constant-speed direct-current motors,** and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

565 In **constant-potential transformers,** the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage.

566 In **converters, dynamotors, motor-generators and frequency converters,** the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal voltage at rated load.

567 In **transmission lines, feeders etc.,** the regulation is the change in the voltage at the receiving end between rated non-inductive load and no load, with constant impressed voltage upon the sending

end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

568 In **steam engines, steam turbines and internal combustion engines,** the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed, to the rated-load speed in passing slowly from rated load to no load (with constant conditions at the supply.)

569 If the test is made by passing suddenly from rated load to no load, the immediate percentage speed regulation so derived shall be termed the **fluctuation.**

570 In **a hydraulic turbine,** or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation in speed in passing slowly from rated load to no load (at constant head of water), to the rated-load speed.

571 In **a generator unit,** consisting of a generator combined with a prime mover, the speed or voltage regulation should be determined at constant conditions of the prime mover; *i.e.* constant steam-pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

CONDITIONS FOR TESTS OF REGULATION

580 **Speed and Frequency.** The regulation of generators is to be determined at constant speed, and of alternating-current apparatus at constant frequency.

581 **Power Factor.** In apparatus generating, transforming or transmitting alternating currents, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is to a load in which the current is in phase with the *e.m f.* at the output side of the apparatus.

582 **Wave Form.** In the regulation of alternating-current machinery receiving electric power, a sine wave of voltage is assumed, except where expressly specified otherwise. See **§405.**

583 **Excitation.** In commutating machines, rectifying machines, and synchronous machines, such as direct-current generators and motors, as well as in alternating-current generators, the regulation is to be determined under such conditions as to maintain the field adjustment constant at that which gives rated-load voltage at rated-load current, as follows:

(1) In the case of separately-excited field magnets—constant excitation.

(2) In the case of shunt machines, constant resistance in the shunt-field circuit.

(3) In the case of series or compound machines, constant resistance shunting the series-field windings.

584 **Tests and Computation of Regulation of A-C. Generators.**

Any one of the three following methods may be used. They are given in the order of preference.

Method a.

The regulation can be measured directly, by loading the generator at the specified load and power factor, then reducing the load to zero, and measuring the terminal voltage, with speed and excitation adjusted to the same values as before the change. This method is not generally applicable for shop tests, particularly on large generators, and it becomes necessary to determine the regulation from such other tests as can be readily made.

585 **Method b.**

This consists in computing the regulation from experimental data of the open-circuit saturation curve and the zero-power-factor saturation curve. The latter curve, or one approximat-

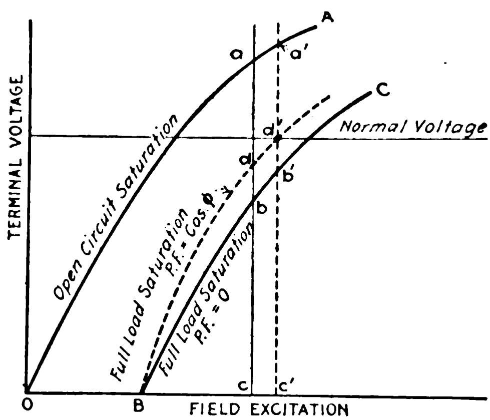


FIG. 1

ing very closely to it, can be obtained by running the generator with over excitation on a load of idle-running under-excited synchronous motors. The power factor under these conditions is very low and the load saturation curve approximates very closely the zero power factor saturation curve. From this curve and the open circuit curve, points for the load saturation curve, for any power factor, can be obtained by means of vector diagrams.

To apply Method b, it is necessary to obtain from test, the open-circuit saturation curve OA, Fig. 1, and the saturation curve BC at zero power factor and rated-load current. At any given excitation Oc, the voltage that would be induced on open circuit is ac, the terminal voltage at zero power factor is bc, and the apparent internal drop is ab. The terminal voltage dc at any other power factor can then be found by drawing an e.m.f. diagram* as in Fig. 2, where ϕ is

***Method b, for deducing the load saturation curve, at any assigned power factor, from no-load and zero-power-factor saturation curves obtained by test, must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.**

an angle such that *cos* ϕ is the power factor of the load, *b e* the resistance drop (IR) in the stator winding, *ba* the total internal drop, and *ac* the total induced voltage; *ba* and *ac* being laid off to correspond with the values obtained from Fig. 1. The terminal voltage at power factor *cos* ϕ, is then *cb* of Fig. 2, which, laid off in Fig. 1, gives point *d*. By finding a number of such points, the curve *Bdd'* for power factor *cos* ϕ is obtained and the regulation at this power factor (expressed in per cent) is $\frac{100 \times a'd'}{d'c'}$, since a' d' is the rise in voltage when the load at power factor *cos* ϕ is thrown off at normal voltage c' d'.

Generally, the ohmic drop can be neglected, as it has very little influence on the regulation, except in very low-speed machines where the armature resistance is relatively high, or in some cases where regulation at unity power factor is being estimated. For low power factors, its effect is negligible in practically all cases. If

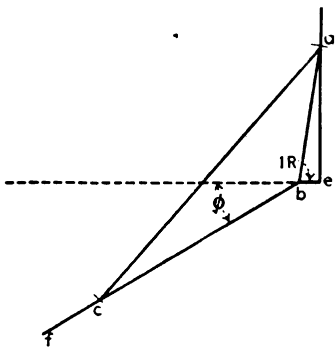


FIG. 2

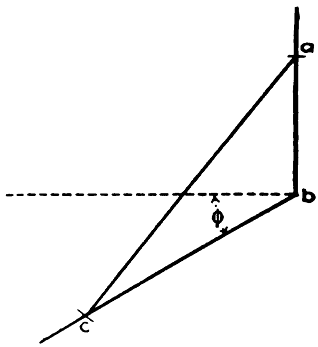


FIG. 3

resistance is neglected, the simpler e.m.f. diagram, Fig. 3, may be used to obtain points on the load saturation curve for the power factor under consideration.

586 **Method c.**

Where it is not possible to obtain by test a zero-power-factor saturation curve as in Method b, this curve can be estimated closely from open-circuit and short-circuit curves, by reference to tests at zero power factor on other machines of similar magnetic circuit. Having obtained the estimated zero-power-factor curve, the load saturation for any other power factor is obtained as in method b.

Thus Method c is the same as Method b; except that the zero-power-factor curve must be estimated. This may be done as follows. In Fig. 4. *OA* is the open-circuit saturation curve and *OE* the short-circuit line as shown by test. The zero-power-factor curve corresponding to any given current *BF* will start from point *B*, and for machines designed with low saturation and low reactance, will follow parallel to *OA* as shown by the dotted curve *BD*, which is *OA* shifted horizontally parallel to itself by the distance *OB*. In high-speed machines, or in others

having low reactance and a low degree of saturation in the magnetic circuit, the zero-power-factor curve will lie quite close to *BD*, particularly in those parts that are used for determining the regulation. This is the case with many turbo-generators and high-speed water-wheel generators. In many cases, however, the zero-power-factor curve will deviate from *BD*, as shown by *BC*, and the deviation will be most pronounced in machines of high reactance, high saturation, and large magnetic leakage. The position of the actual curve *BC* with relation to *BD*, can be approximated with sufficient exactness by investigating the corresponding relation as obtained by test at zero power factor on machines of similar characteristics and magnetic circuit. Or curve *BC* can be calculated by methods based on the results of tests at zero power factor. After *BC* has been obtained, the saturation curve and regulation for any other power factor can be derived as in Method (b).

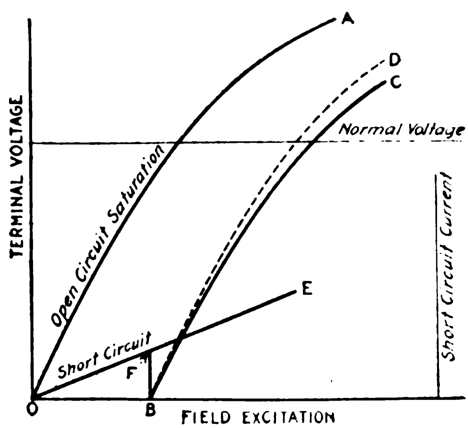


FIG. 4

587 Tests and Computation of Regulation for Constant-Potential Transformers.

The regulation can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power factor. This method is not generally applicable for shop tests, particularly on large transformers.

The regulation for any specified load and power factor can be computed from the measured impedance watts and impedance volts, as follows:

Let:

P = impedance watts, as measured in the short-circuit test at 75°C.

E_z = impedance volts, as measured in the short-circuit test.

IX = Reactance Drop in Volts.

I = Rated Primary Current.

E = Rated Primary Voltage.

q_r = percent drop in phase with current.
q_x = percent drop in quadrature with current.

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}$$

$$q_r = 100\frac{P}{EI}$$

$$q_x = 100\frac{IX}{E}$$

588 Then—

1. For **unity power factor**, we have approximately:-

$$\text{Per cent regulation} = q_r + \frac{q^2_x}{200}$$

589 2. For **inductive loads** of power-factor m and reactive-factor n,

$$\text{Per cent regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}$$

TRANSFORMER CONNECTIONS

SINGLE-PHASE TRANSFORMERS

600 **Marking of Leads.**

The leads of single-phase transformers shall be distinguished from each other by marking the high-voltage leads with the letters A and B, and the low-voltage leads with the letters X and Y. They shall be so marked that the potential difference between A and B shall have the same direction at any instant as the potential difference between X and Y.

In accordance with the above rule, the terminals of single-phase transformers shall be marked as follows:

601 (1) High- and Low-Voltage Windings in Phase:

A ——— B
X ——— Y

602 (2) High- and Low-Voltage Windings 180 deg. Apart in Phase:

A ——— B
Y ——— X

603 **To operate transformers thus marked in parrallel,** it is only necessary to connect similarly marked terminals together, (provided that the reactances and resistances of the transformers are such as to permit of parallel operation).

604 **Single-Phase Transformers with More Than Two Windings.**

Transformers possessing three or more windings (each being provided with separate out-going leads), shall have the leads con-

nected to two of their windings, lettered in accordance with the preceding paragraph. The remaining leads shall be distinguished from the others by a subscript. For example, transformers possessing four secondary leads connected to two distinct similar windings for multiple-series operation, shall be lettered as follows:

$$\begin{array}{c} A \text{———} B \\ \left\{ \begin{array}{c} X \text{———} Y \\ X_1 \text{———} Y_1 \end{array} \right\} \end{array}$$

This indicates that the low-voltage winding consists of two disconnected parts, one part having terminals XY and the other part having terminals $X_1 Y_1$. For multiple connection, X and X_1 are connected together and Y and Y_1 are connected together. For series connection, Y is connected to X_1.

605 **Neutral Lead**

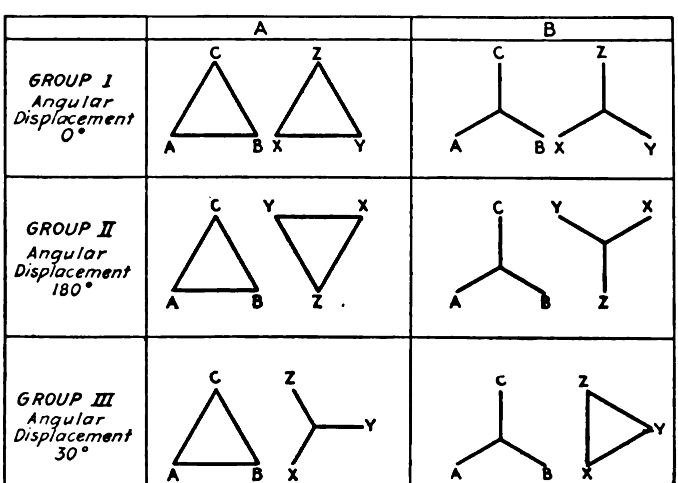
An out-going 50 per cent. (neutral) tap lead should be lettered N.

606 **Internal Connections**

The manufacturer shall furnish a complete diagrammatic sketch of internal connections, and all taps and terminals of the transformer shall be marked to correspond with numbers or letters in the sketch.

THREE-PHASE TRANSFORMERS

607 Three-phase transformers ordinarily have three or four leads for high-voltage, and three or four leads for low-voltage windings. To distinguish the various leads from each other, and also to distinguish between the various phase relations obtainable, the three high-voltage leads should be lettered A B C and the three low-voltage leads X Y Z. In addition, it should be distinctly stated in which of the three groups given in the following diagram the transformer belongs.



608 The rules given above for **single-phase transformers in regard to the neutral tap,** (See **§605**) and also in regard to internal connections, (See **§600** to **§604**) are applicable to three-phase transformers.

609 **Angular Displacement.**

The angular displacement between high- and low-voltage windings, is the angle in the diagram in **§607**, between the lines passing from the neutral point through A and X respectively. Thus, in Group 1, the angular displacement is zero degrees. In Group 2, the angular displacement is 180°, and in Group 3 the angular displacement is 30°.

610 **Parallel Operation of Three-Phase Transformers.**

Three-phase transformers, lettered in accordance with the above rules, will operate correctly in parallel, if at their rated loads, their percentage resistance drops are equal, and their percentage reactance drops, are equal. It is furthermore necessary that the angular displacements between high-voltage and low-voltage windings shall be equal, *i.e.* that the transformers shall belong to the same group in the diagram in **§607**. It is then only necessary to connect together similarly marked leads.

INFORMATION ON THE RATING PLATE OF A MACHINE

620 It is recommended that the rating plate of machines which comply with the Institute rules shall carry a distinctive special sign, such as " A.I.E.E. **1915** Rating" or "A15" Rating.

621 The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature of reference. See **§§287, 305, 308** and **309.**

622 The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

623 The rating plate, in addition to the name of the manufacturer and the serial number, should give the following information.*

624 **Generator, Direct-Current.**

Shunt, series, or compound.
Output, in kw., with statement as to the kind of rating.
Terminal pressure, in volts.
Current, in amperes.
Speed, in revolutions per minute.

625 **Motor, Direct-Current.**

Shunt, series, or compound.
Output, in kw., with statement as to the kind of rating.
Terminal pressure, in volts.
Current, approximate, in amperes.
Speed, in revolutions per minute.

*Information, for which space on the rating plate cannot be provided, shall be furnished on a supplementary rating certificate.

626 **Transformer.**

Frequency, in cycles per second.

Number of phases.

Output at the secondary terminals in kv-a., with statement as to the kind of rating.

High pressure, in volts.

Low pressure, in volts. See §§**202, 203** and **204**

Lead markings and diagram of internal connections, as set forth in §**600** to **609.**

627 **Alternator.**

Frequency, in cycles per second.

Number of poles.

Number of phases.

Output, in kv-a., with statement as to the kind of rating.

Power-factor corresponding to rated output.

Pressure between terminals, in volts, corresponding to the rated output.

Current in amperes.

Speed in revolutions per minute.

628 **Synchronous Motor.**

Frequency, in cycles per second.

Number of poles.

Number of phases.

Mechanical output, in kw., with statement as to the kind of rating.

Pressure between terminals, in volts, corresponding to the rated output.

Current in amperes.

If the motor is intended to work with a power factor different from unity, the necessary information shall be given.

Speed, in revolutions per minute.

629 **Synchronous Converter.**

Frequency in cycles per second.

Number of poles.

Number of phases.

Output at commutator in kilowatts, with statement as to kind of rating.

D.c. terminal pressure in volts.

Current from commutator in amperes.

Speed in revolutions per minute.

630 **Induction Motor.**

Frequency, in cycles per second.

Number of poles.

Number of phases.

Mechanical output, in kw., with statement as to the kind of rating.

Pressure between terminals, in volts.

Current, in amperes.

Speed, in revolutions per minute, at rated output.

STANDARDS FOR WIRES AND CABLES

TERMINOLOGY*

635 **Wire.**—A slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

636 **Conductor.**—A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents.

Rolled conductors (such as busbars) are, of course, conductors, but are not considered under the terminology here given.

637 **Stranded Conductor.**—A conductor composed of a group of wires, or of any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together.

638 **Cable.**—(1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable).

The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one, and, in practise, it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead, or with steel wires or bands.

639 **Strand.**—One of the wires, or groups of wires, of any stranded conductor.

640 **Stranded Wire.**—A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If used as a wire, for example in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord," defined below.

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*From Circular No. 37 of the Bureau of Standards.

641 **Cord**—A small and very flexible cable, substantially insulated to withstand wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Rubber is used as the insulating material for many classes of cords.

642 **Concentric Strand.**—A strand composed of a central core surrounded by one or more layers of helically-laid wires or groups of wires.

643 **Concentric-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid wires.

644 **Rope-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid groups of wires.

This kind of cable differs from the preceding in that the main strands are themselves stranded.

645 **N-Conductor Cable.**—A combination of N conductors insulated from one another.

It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable" etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in definition §638 above.)

646 **N-Conductor Concentric Cable.**—A cable composed of an insulated central conducting core with (N — 1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

This kind of cable usually has only two or three conductors. Such cables are used for carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

647 **Duplex Cable.**—Two insulated single-conductor cables, twisted together.

They may or may not have a common insulating covering.

648 **Twin Cable.**—Two insulated single-conductor cables laid parallel, having a common covering.

649 **Triplex Cable.**—Three insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

650 **Twisted Pair.**—Two small insulated conductors, twisted together, without a common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

651 **Twin Wire.**—Two small insulated conductors laid parallel having a common covering.

*SPECIFICATION OF SIZES OF CONDUCTORS

652 **The sizes of solid wires** shall be stated by their diameter in mils, the American Wire Gage (Brown and Sharpe) sizes being taken as standard. The sizes of stranded conductors shall be stated by their cross-sectional area in circular mils. For brevity, in cases where the most

careful specification is not required, the sizes of solid wires may be stated by the gage number in the American Wire Gage, and the sizes of stranded conductors smaller than 250,000 circular mils (*i.e.*, No. 0000 A.W.G. or smaller) may likewise be stated by means of the gage number in the American Wire Gage of a solid wire having the same cross-sectional area. Futhermore, an exception is made in the case of "Flexible Stranded Conductors," for which see §655 below. In **stating large cross-sections,** it is sometimes convenient to use a circular inch (507 sq. mm.) instead of 1,000,000 circular mils.

STRANDING

653 Cables not requiring special flexibility shall be stranded in accordance with the following table.

TABLE XII
Standard Stranding of Concentric-Lay Cables

SIZE (See Note 1.)	Number of Wires. A Bare Cables for AERIAL USE*	B Weatherproof Cables for AERIAL USE*	C Insulated Cables
2.0 Cir. Inches	91	91	127
1.5	61	61	91
1.0	61	61	61
0.6	37	37	61
0.5	37	37	37
0.4	19	19	37
0000 A. W. G.	7	19	19
00	7	7	19
2	(See Note 2)	(See Note 2)	7
9	(See Note 2)	(See Note 2)	(See Note 2)

(1) For intermediate sizes, use stranding for next larger size.
(2) Solid Wire is recommended.

*Tentatively adopted pending ratification by other societies interested.

654 **Sectional Area of Cables.** The cross-sectional area of a cable shall be considered to be the sum of the cross-sectional areas of its component wires, when laid out straight and measured perpendicular to their axes.

655 **Flexible Stranding.** Conductors of special flexibility should ordinarily be made with wires of regular A.W.G. sizes, the number of wires and size being given. The approximate gage number or ap-

proximate circular mils of such flexible stranded conductors may be stated. The following stranding table is suggested.

TABLE XIII

Proposed Standard Stranding of Flexible Cables*

Nearest A. W. G. Size (See Note 1)	Circular Mils	Number of Wires	Size of Each Wire A. W. G.	Make-up (See Note 2)
–	1,102,941	427	16	61x7
–	874,496	427	17	"
–	693,448	427	18	"
–	549,976	427	19	"
–	436,394	427	20	"
–	345,913	427	21	"
–	274,390	427	22	"
–	264,698	259	20	37x7
0000	209,816	259	21	"
000	166,433	259	22	"
00	135,926	133	20	19x7
0	107,743	133	21	"
1	85,466	133	22	"
2	67,764	133	23	"
3	53,732	133	24	"
4	39,695	49	21	7x7
5	31,487	49	22	"
6	24,966	49	23	"
7	19,796	49	24	"
8	15,700	49	25	Optional (See Note 3)
9	12,451	49	26	"
10	9,854	49	27	"
11	7,830	49	28	"
12	6,208	49	29	"
Smaller		To equal required size	30	Bunched

Note 1. The A. W. G. sizes are approximated within 5 per cent.
Note 2. 61x7 signifies a rope-lay cable composed of 61 strands of 7 wires each.
Note 3. Rope-lay or bunched.

* This table is offered for consideration but will not be recommended for final adoption until ratified by other societies interested. The addition of another Table giving a further degree of flexibility is under consideration. The stranding of No. 4 A. W. G. and smaller sizes, is particularly open for discussion.

656 **Correction for Lay.** The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay (*i.e.*, the pitch of the twist of the wires). Two per cent shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment should be calculated and not assumed.

The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

CONDUCTIVITY OF COPPER.

675 The following I. E. C. rules are adopted:*

The following shall be taken as normal values for standard annealed copper:

(1) At a temperature of 20°C., the resistance of a wire of standard annealed copper one meter in length and of a uniform section of 1 square millimeter is 1/58 ohm = 0.017241 . . . . ohm.

(2) At a temperature of 20°C., the density of standard annealed copper is 8.89 grams per cubic centimeter.

(3) At a temperature of 20°C, the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between two potential points rigidly fixed to the wire, is 0.00393 = 1/254.45 . . . . per degree centigrade.

(4) As a consequence, it follows from (1) and (2) that, at a temperature of 20 °C. the resistance of a wire of standard annealed copper of uniform section, one meter in length and weighing one gram, is (1/58) × 8.89 = 0.15328 . . . . . . ohm.†§

676 **Copper Wire Tables.** The copper-wire Tables published by the Bureau of Standards in Circular No. 31 are adopted. These Tables are based upon the I. E. C. rules stated in §**675**.

HEATING AND TEMPERATURE OF CABLES.

677 **Maximum Safe Limiting Temperatures.**

The maximum safe limiting temperature in degrees C. at the surface of the conductor in a cable shall be:—

For impregnated paper insulation	(85—E)
" varnished cambric	(75—E)
" rubber insulation	(60—0.25E)

where E represents the r.m.s. operating e.m.f. in kilovolts between conductors.

Thus, at a working pressure of 3.3 kv., the maximum safe limiting temperature at the surface of the conductor, or conductors, in a cable would be:—

For impregnated paper	81.7°C.
" varnished cambric	71.7°C.
" rubber insulation	59.2°C.

ELECTRICAL TESTS.

678 **Lengths Tested.** Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

*See I. E. C. Publication No. 28 "International Standard of Resistance for Copper" March 1914.

†Paragraphs (1) and (4) of §675 define what are sometimes called "volume resistivity," and "mass resistivity" respectively. This may be expressed in other units as follows:— volume resistivity = 1.7241 microhm-cm. (or microhms in a cm. cube) at 20 °C. = 0.67879 microhm-inch at 20 °C., and mass resistivity = 875.20 ohms (mile, pound) at 20 °C.

§For detailed specifications of commercial copper, see the "Standard Specifications" of the American Society for Testing Materials.

679 **Immersion in Water.** Electrical tests of insulated conductors not enclosed in a lead sheath, shall be made while immersed in water after an immersion of twelve (12) hours, if insulated with rubber compound, or if insulated with varnished cambric. It is not necessary to immerse in water insulated conductors enclosed in a lead sheath.

In multiple-conductor cables, without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

680 **Dielectric-Strength Tests. Object of Tests.** Dielectric tests are intended to detect weak spots in the insulation and to determine whether the dielectric strength of the insulation is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

The initially-applied voltage must not be greater than the working voltage, and the rate of increase shall not be over 100 per cent in 10 seconds.

681 **Factor of Assurance.** The factor of assurance of wire or cable insulation shall be the ratio of the voltage at which it is tested to that at which it is used.

682 **Test Voltage.** The dielectric strength of wire and cable insulation shall be tested at the factory, by applying an alternating test voltage between the conductor and sheath or water.

683 **The Magnitude and Duration of the Test Voltage** should depend upon the dielectric strength and thickness of the insulation, the length and diameter of the wire or cable, and the assurance factor required, the latter in turn depending upon the importance of the service in which the wire or cable is employed

684 **The following test voltages** shall apply unless a departure is considered necessary, in view of the above circumstances. Rubber covered wires or cable for voltages up to 7 kv. shall be tested in accordance with the National Electric Code. Standardization for higher voltages for rubber insulated cables is not considered possible at the present time.

Varnished cambric and impregnated paper insulated wires or cables shall be tested at the place of manufacture for five (5) minutes in accordance with the Table XIV below.

TABLE XIV

Recommended Test Kilovolts Corresponding to Operating Kilovolts

Operating kv.	Test kv.	Operating kv.	Test kv.
Below 0 5	2.5*	5	14
0.5	3	10	25
1	4	15	35
2	6.5	20	44
3	9	25	53
4	11.5		

*The minimum thickness of insulation shall be 1/16″ (1-6 mm.)

Different engineers specify different thickness of insulation for the same working voltages. Therefore, at the present time the test kv. corresponding to working kv. given in Table XIV are based on the **minimum** thickness of insulation specified by engineers and operating companies.†

685 **The Frequency of the Test Voltage** shall not exceed 100 cycles per second, and should approximate as closely as possible to a sine wave. The source of energy should be of ample capacity.

686 **Where Ultimate Break-Down Tests** are required, these shall be made on samples not more than 6 meters (20 ft.) long. The maximum allowable temperature at which the test is made for the particular type of insulation and the particular working pressure, shall not be greater than the temperature limits given in **§ 677**.

687 **Multiple-Conductor Cables.** Each conductor of a multiple-conductor cable shall be tested against the other conductors connected together with the sheath or water.

INSULATION RESISTANCE

688 **Definition.** The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

689 **Insulation Resistance** shall be expressed in megohms for a specified length (as for a kilometer, or a mile, or one thousand feet), and shall be corrected to a temperature of 15.5° C. using a temperature coefficient determined experimentally for the insulation under consideration.

690 **Linear Insulation Resistance,** or the insulation resistance of Unit Length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet.

691 **Megohms Constant.** The Megohms Constant of an insulated conductor shall be the factor "K" in the equation

$$R = K \log_{10} \frac{D}{d}$$

where R = The insulation resistance, in megohms, for a specified unit length.

D = Outside diameter of insulation.

d = Diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

692 **Test.** The apparent insulation resistance should be measured after the dielectric-strength test, measuring the leakage current after a one-minute electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained positive to the sheath or water.

†The Standards Committee does not commit itself to the principle of basing test voltages on working voltages, but it is not yet in possession of sufficient data to base them upon the dimensions and physical properties of the insulation.

693 **Multiple-Conductor Cables.** The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from such conductor to all the other conductors in multiple with the sheath or water.

CAPACITANCE OR ELECTROSTATIC CAPACITY

694 **Capacitance** is ordinarily expressed in microfarads. Linear Capacitance, or Capacitance per unit length, shall be expressed in Microfarads per unit length (kilometer, or mile, or one thousand feet) and shall be corrected to a temperature of 15.5° C.

695 **Microfarads Constant.** The Microfarads Constant of an insulated conductor shall be the factor " K " in the equation

$$C = \frac{K}{\operatorname{Log}_{10} \frac{D}{d}}$$

where C = the capacitance in microfarads per unit length.

D = the outside diameter of insulation.

d = the diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

696 **Measurement of Capacitance.** The Capacitance of low-voltage cable, shall be measured by comparison with a standard condenser. For long lengths of high-voltage cables, where it is necessary to know the true capacitance, the measurement should be made at a frequency approximating the frequency of operation.

697 **Paired Cables.** The capacitance shall be measured between the two conductors of any pair, the other wires being connected to the sheath or ground.

698 **Electric Light and Power Cables.** The capacitance of low-voltage cables is generally of but little importance. The capacitance of high-voltage cables should be measured between the conductors, and also between each conductor and the other conductors connected to the lead sheath or ground.

699 **Multiple-Conductor Cables** (not paired). The capacitance of each conductor of a multiple-conductor cable shall be the capacitance measured from such conductor to all of the other conductors in multiple with the sheath or the ground.

STANDARDS FOR SWITCHES AND OTHER CIRCUIT-CONTROL APPARATUS*

SWITCHES

720 **The following Rules apply to Switches** of above 600 volts. (For 600 volts and below, see National Electric Code.†)

721 **Definition.** A switch is a device for making, breaking, or changing connections in an electric circuit.

722 **Rating.**

(a) By amperes to be carried with not more than 30 °C. rise on contacts and current-carrying parts.

(b) By normal voltage of circuit on which it may be used.

723 **Performance and Tests.**

(a) **Heating Test** with rated current applied continuously until temperature is constant; ambient temperature 40 °C.

(b) **Dielectric Test** at 2½ times rated voltage plus 2000. See **§509.**

CIRCUIT BREAKERS

724 **Definition.** A device designed to open a current-carrying circuit without injury to itself. A circuit breaker‡ may be:

(a) An automatic circuit-breaker, which is designed to trip automatically under any predetermined condition of the circuit, such as an underload or overload of current or voltage.

(b) A manually tripped circuit-breaker, which is designed to be tripped by hand.

Both types of operation may be combined in one and the same device.

725 **Rating.**

(a) By normal current-carrying capacity.

(b) By normal voltage.

(c) By amperes which it can interrupt at normal voltage of the circuit.

726 **Performance and Tests.** The heating test shall be made with normal current. In oil circuit breakers the same oil must be used for heating tests as for rupturing tests. The rise of temperature at the contacts shall not exceed 30 °C. The Rise on tripping solenoids and accessory parts not to exceed 50 °C. Ambient temperature of reference, 40 °C.

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*These rules do not apply to magnetically-operated or air-operated switches used for motor control.

†By the term "Code" is meant "National Electrical Code" as recommended by the National Fire Protection Association.

‡These rules refer only to circuit breakers of above 550 volts. For 550 volts and below, see the National Electric Code.

727 **Dielectric Test.** Same as **§723.**

728 **Rupturing Test** must be made with the current specified under **§725** (c), and at normal voltage.

NOTE. Although circuit breakers should be considered as devices alone, no account being taken, in the rating, of the system on which they are to be used: yet in applying circuit breakers to any given service, it may be necessary to take into account the system on which they are to be used, with all its characteristics.

Allowances must be made for the reactance, resistance, etc., of the circuit to be controlled, as these have a direct bearing on the maximum current flow.

In some systems it has been found that the pressure rises so high during switching, that higher insulation tests than that specified in **§723** should be given.

FUSES

(For circuits up to and including 600 volts, see **National Electric** Code)

729 **Definition.** A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

NOTE. (The terminals, tubes, etc. which go with the fuse proper are included in the definition).

730 **Rating.** Fuses shall be rated at the maximum current which they are required to carry continuously, and at the normal voltage of the circuit on which they are designed to be used.

Fuses may be divided into two classes:

(1) Those designed to protect the circuit and apparatus both against short circuit and against definite amounts of overload (*e.g.* fuses of the National Electric Code which open on 25 per cent overload).

(2) Those designed to protect the system only against short circuits; (*e.g.* expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

731 **Temperature.** Coils or windings (such as accompany fuses of the magnetic blow-out type) should not exceed the limits set for machine coils having the same character of insulation. (See **§§376 to 379**). The highest temperature for the fuse proper should not exceed the safe limit for the material employed (*e.g.* the temperature of the fibre tube of an enclosed fuse should not exceed the safe limit for this material, but an open-link metal fuse may be run at any temperature which will not injure the fuse material; except that no application of the above rule shall contravene the National Electric Code).

732 **Test.** For fuses intended for use on circuits of small capacity, or in protected positions on systems of large capacity see Nation-

NOTE. Complete standardization of these fuses above 600 volts, according to the method of the National Electric Code, is not advisable at this time, but is expected to be accomplished by an eventual extension of the National Electric Code. Until such extension is made, the following definitions and ratings may be followed.

al Electric Code For large power fuses intended for service similar to that required of circuit breakers, see **§724** to **728**, or the National Electric Code, as far as the latter applies.

LIGHTNING ARRESTERS

733 **Definition.** A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

734 **Rating.** Arresters shall be rated by the voltage of the circuit on which they are to be used

Lightning arresters may be divided into two classes:

(a) Those intended to discharge for a very short time.

(b) Those intended to discharge for a period of several minutes.

735 **Performance and Tests.** Dielectric Test same as **§723.**

The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

(c) In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60-cycle a-c. excitation.

(d) The equivalent sphere gap under disruptive discharge shall also be measured, using a considerable quantity of electricity.

(e) The endurance of the arrester to continuous surges shall be tested.

PROTECTIVE REACTORS

736 **Definition.** A reactor (See **§82** and **214**) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short-circuit conditions.

737 **Rating.**

(a) In kilovolt-amperes absorbed by normal current.

(b) By the normal current, frequency and line (delta) voltage for which the reactor is designed.

(c) By the current which the device is required to stand under short-circuit conditions.

738 **Performance and Tests.**

The Heat Test shall be made with normal current and frequency applied until the temperature is constant. The temperature should not exceed the safe limits for the materials employed. See **§§376** to **379**.

739 **Dielectric Test.** 2½ times line voltage plus 2000, for one minute, from conductor to ground.

Note. The reactor shall be so designed as to be capable of withstanding, without mechanical injury, rated current at normal frequency, suddenly applied.

RESISTOR OR RHEOSTAT

740 **Definition.** Any device heretofore commonly known as a resistance, used for operation or control. (**§81**) See National Electric Code.

INSTRUMENT TRANSFORMERS

741 **Definition.** An instrument transformer is a transformer for use with measuring instruments, in which the conditions in the primary circuit as to current and voltage are represented with high numerical accuracy in the secondary circuit.

Under this heading and for more general use:

(a) A current transformer is a transformer designed for series connection in its primary circuit with the ratio of transformation appearing as a ratio of currents.

(b) A potential (voltage) transformer is a transformer designed for shunt or parallel connection in its primary circuit, with the ratio of transformation appearing as a ratio of potential differences (voltages).

For further definitions relative to instrument transformers, see **205-207.**

For the dielectric test of potential transformers, see **§500,** and for the dielectric test of current transformers, see **§509.**

Further standards concerning instrument transformers are still under discussion.

STANDARDS FOR ELECTRIC RAILWAYS

DEFINITIONS

760 **Transmission System:** When the current generated for an electric railway is changed in kind or voltage, between the generator and the cars or locomotives, that portion of the conductor system carrying current of a kind or voltage substantially different from that received by the cars or locomotives, constitutes the ***transmission system.****

761 **Distribution System:** That portion of the conductor system of an electric railway which carries current of the kind and voltage received by the cars or locomotives, constitutes the ***distribution system.****

762 **Substation:** A substation is a group of apparatus or machinery which receives current from a transmission system, changes its kind or voltage, and delivers it to a distribution system.

RATING OF RAILWAY SUBSTATION MACHINERY

763 **Continuous Rating.** The rating of a substation machine shall be the kv-a. output at a stated power factor input, which it will deliver continuously with temperatures or temperature rises not exceeding the limiting values given in Sections **376** and **379** and also fulfilling the other requirements set forth in these rules and summarized in Section **260**.

764 **Momentary Loads.** These machines should be capable of carrying a load of twice their rating for one minute, after a continuous run at rated load, without disqualifying them for continuous service.

765 **Nominal Rating.** Where the continuous rating is inconvenient, the following nominal rating may be used. The nominal rating of a substation machine shall be the kv-a. output at a stated power factor input, which, having produced a constant temperature in the machine may be increased 50 per cent. for two hours, without producing temperatures or temperature rises exceeding by more than 5°C. the limiting values given in §**376** and **379**. These machines should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked " nominal rating."

CONDUCTOR AND RAIL SYSTEMS.

766 **Contact Conductors.** That part of the distribution system other than the traffic rails, which is in immediate electrical contact with

*These definitions are identical in sense, although not in words, with those of the Interstate Commerce Commission, as given in their Classification of Accounts for Electric Railways.

the circuits of the cars or locomotives constitutes the contact conductors.

767 **Contact Rail:** A rigid contact conductor.

768 OVERHEAD CONTACT RAIL: A contact rail above the elevation of the maximum equipment line.†

769 THIRD RAIL: A contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

770 CENTER CONTACT RAIL: A contact conductor placed between the track rails, having its contact surface above the ground level.

771 UNDERGROUND CONTACT RAIL: A contact conductor placed beneath the ground level.

772 GAGE OF THIRD RAIL: The distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the *contact surface* of the third rail.

773 ELEVATION OF THIRD RAIL: The elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

774 STANDARD GAGE OF THIRD RAILS: The gage of third rails shall be not less than 26 inches (66 cm.) and not more than 27 inches (68.6 cm.).

775 STANDARD ELEVATION OF THIRD RAILS: The elevation of third rails shall be not less than 2¾ inches (70 mm.), and not more than 3½ inches (89 mm.).

776 THIRD RAIL PROTECTION: A guard for the purpose of preventing accidental contact with the third rail.

777 **Trolley Wire:** A flexible contact conductor, customarily supported above the cars.

778 **Messenger Wire or Cable:** A wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

779 **Classes of Construction:** Overhead trolley construction will be classed as *Direct Suspension* and *Messenger or Catenary Suspension.*

780 DIRECT SUSPENSION: All forms of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

781 MESSENGER OR CATENARY SUSPENSION: All forms of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *Simple Catenary, i.e.*, by primary messengers, or in *Compound Catenary, i.e.*, by secondary messengers.

782 SUPPORTING SYSTEMS shall be classed as follows:

783 SIMPLE CROSS-SPAN SYSTEMS: Those systems having at each support a single flexible span across the track or tracks.

†The contour which embraces cross-sections of all rolling stock under all normal operating conditions.

784 MESSENGER CROSS-SPAN SYSTEMS: Those systems having at eac support two or more flexible spans across the track or tracks, the uppe span carrying part or all of the vertical load of the lower span.

785 BRACKET SYSTEMS: Those systems having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

786 BRIDGE SYSTEMS: Those systems having at each support a rigid member, supported at both sides of the track or tracks.

787 STANDARD HEIGHT OF TROLLEY WIRE ON STREET AND INTERURBAN RAILWAYS: It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 feet (5.5m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 feet (6.4m.) above the top of rail, under conditions of maximum sag.

RAILWAY MOTORS

RATING

800 **Nominal Rating:** The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90 °C. at the commutator, and 75 °C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100 °C.*

801 The statement of the nominal rating shall also include the corresponding voltage and armature speed.

802 **Continuous Rating:** The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at ½, ¾ and full voltage respectively, without exceeding the specified temperature rises (see §805), when operated on stand te.t with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to

*This definition differs from that in the 1911 edition of the Rules, principally by the substitution of a kilowatt rating for the horse-power rating and the omission of a reference to a room temperature of 25 °C. The horse-power rating of a railway motor may, for practical purposes, be taken as $\frac{4}{3}$ of the kilowatt rating. On account of the hitherto prevailing practise of expressing mechanical output in horse-power, it is recommended that, for the present, the capacity be expressed both in kilowatts and in horse-power, a double rating, namely,

kw.————approx. equiv. h.p.————

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the capacity in horse power.

define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

803 **Maximum Input.** The subject of momentary loads for railway motors is under investigation.

TEMPERATURE LIMITATIONS

804 **The allowable temperature** in any part of a motor in service will be governed by the kind of material with which that part is insulated. In view of space limitations, and the cost of carrying dead weight on cars, it is considered good practice to operate railway motors for short periods at higher temperatures than would be advisable in stationary motors. The following temperatures are permissible:

TABLE XV
Operating Temperatures of Railway Motors

Class of Material See §376 to 379.	Maximum Observable Temperature of windings when in continuous service.	
	By Thermometer See §345	By Resistance
A	85	110
B	100	130

For infrequent occasions, due to extreme ambient temperatures, it is permissible to operate at 15° higher temperature.

805 With a view to not exceeding the above temperature limitations, the continuous ratings shall be based upon the **temperature rises** tabulated below:

TABLE XVI
Stand-Test Temperature Rises of Railway Motors*

Class of Material See §376 to 379	Temperature Rises of windings	
	By Thermometer See §345	By Resistance
A	65	85
B	80	105

*The temperature rise in service may be very different from that on stand test. See §1104 for relation between stand test and service temperatures, as affected by ventilation

806 **Field-Control Motors.** The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

CHARACTERISTIC CURVES

810 **The Characteristic Curves** of railway motors shall be plotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of a-c. motors, the power factor shall also be plotted as ordinates.

811 **Characteristic curves of direct-current motors** shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

812 **In the case of field-control motors,** characteristic curves shall be given for all operating field connections.

EFFICIENCY AND LOSSES

815 **The efficiency** of railway motors shall be deduced from a determination of the losses enumerated in **§816** to **820.** (See also **§ 1100** and **1101.**)

816 **The copper loss** shall be determined from resistance measurements corrected to 75° C.

817 **The no-load core loss, brush friction, armature-bearing friction and windage** shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

818 The **core loss** in d-c. motors shall be separated from the friction and windage losses above described by measuring the power required to drive the motor at any given speed without gears, by running it as a series motor on low voltage and deducting this loss from the sum of the no-load losses at corresponding speed. (See **§1101** for alternative method).

The friction and windage losses under load shall be assumed to be the same as without load, at the same speed.

The core loss under load shall be assumed as follows:

TABLE XVII

Core Loss in d.c. Railway Motors at Various Loads.

Per cent of Input at Nominal Rating	Loss as Per cent of No-load Core Loss
200	165
150	145
100	130
75	125
50	123
25 and under	122

Note:—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above Table.

819 **The brush-contact resistance loss** to be used in determining the efficiency, may be obtained by assuming that the sum of the drops at the contact surfaces of the positive and negative brushes is three volts.

820 The losses in gearing and axle bearings for single-reduction single-geared motors, varies with type, mechanical finish, age and lubrication The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-geared motors.

TABLE XVIII

Losses in Axle Bearings and Single-Reduction Gearing of Railway Motors.

Per Cent of Input at Nominal Rating	Losses as Per Cent of Input
200	3.5
150	3.0
125	2.7
100	2.5
75	2.5
60	2.7
50	3.2
40	4.4
30	6.7
25	8.5

NOTE:—Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

ELECTRIC LOCOMOTIVES

830 **Rating.** Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort and corresponding speeds.

831 **Weight on Drivers.** The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

832 **Nominal Tractive Effort:** The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers, when the motors are operating at their nominal (one-hour) rating.

833 **Continuous Tractive Effort.** The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in **§802**.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for $\frac{1}{2}$ or $\frac{3}{4}$ voltage, but in such cases the voltage shall be clearly specified.

834 **Speed:** The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

See also Appendix II on Additional Standards for Railway Motors.

ILLUMINATION AND PHOTOMETRY

The following Sections, **850** to **895**, are the rules of the Nomenclature and Standards Committee of the Illuminating Engineering Society. They are here included by permission.

850 **Luminous flux** is radiant power evaluated according to its capacity to produce the sensation of light.

851 **The stimulus coefficient** K_λ for radiation of a particular wave-length, is the ratio of the luminous flux to the radiant power producing it.

852 **The mean value of the stimulus coefficient, K_m,** over any range of wave-lengths, or for the whole visible spectrum of any source, is the ratio of the total luminous flux (in lumens) to the total radiant power (in ergs per second, but more commonly in watts).

853 **The luminous intensity** of a point source of light is the solid angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per unit solid angle from that source.

Defining equation:

Let I be the intensity, F the flux and ω the solid angle.

Then $$I = \frac{dF}{d\omega}$$

or, if the intensity is uniform,

$$I = \frac{F}{\omega},$$

854 **Illumination,** on a surface, is the luminous flux-density over that surface, or the flux per unit of intercepting area.

Defining equation:

Let E be the illumination and S the area of the intercepting surface.

Then $$E = \frac{dF}{dS},$$

or, when uniform,

$$E = \frac{F}{S},$$

855 **Candle,** the unit of luminous intensity maintained by the National Laboratories of France, Great Britain, and the United States.[1]

856 **Candle-power,** luminous intensity expressed in candles

1 This unit, which is used also by many other countries, is frequently referred to as the international candle.

857 **Lumen,** the unit of luminous flux, equal to the flux emitted in a unit solid angle (steradian) by a point source of one candle-power.[2]

858 **Lux,** a unit of illumination equal to one lumen per square meter. The C. G. S. unit of illumination is one lumen per square centimeter. For this unit Blondel has proposed the name " Phot." One milli-lumen per square centimeter (milliphot) is a practical derivative of the C. G. S. system. One foot-candle is one lumen per square foot and is equal to 1.0764 milliphots.

859 **Exposure,** the product of an illumination by the time. Blondel has proposed the name " phot-second " for the unit of exposure in the C. G. S. system.

860 **Specific luminous radiation,** the luminous flux-density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per square centimeter.

Defining equation:

Let E′ be the specific luminous radiation.

Then, for surfaces obeying Lambert's cosine law of emission.

$$E' = \pi b_0.$$

861 **Brightness,** b, of an element of a luminous surface from a given position, may be expressed in terms of the luminous intensity per unit area of the surface projected on a plane perpendicular to the line of sight, and including only a surface of dimensions negligibly small in comparison with the distance to the observer. It is measured in candles per square centimeter of the projected area.

Defining equation:

Let θ be the angle between the normal to the surface and the line of sight.

Then $$b = \frac{dI}{dS \cos\theta}$$

862 **Normal brightness,** b_0, of an element of a surface (sometimes called specific luminous intensity) is the brightness taken in a direction normal to the surface.[3]

Defining equation:

$$b_0 = \frac{dI}{dS},$$

or, when uniform, $$b_0 = \frac{I}{S}$$

Brightness may also be expressed in terms of the specific luminous radiation of an ideal surface of perfect diffusing qualities, *i. e.*, one obeying Lambert's cosine law.

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2 A uniform source of one candle emits 4π lumens.

3 In practice, the brightness b of a luminous surface or element thereof is observed, and not the normal brightness b_0. For surfaces for which the cosine law of emission holds, the quantities b and b_0 are equal.

863 **The Lambert, the C. G. S. Unit of brightness,** the brightness of a perfectly diffusing surface radiating or reflecting one lumen per square centimeter. This is equivalent to the brightness of a perfectly diffusing surface having a coefficient of reflection equal to unity and illuminated by one phot.

864 **For most purposes, the millilambert** (0.001 lambert) is the preferable practical unit. A perfectly diffusing surface emitting one lumen per square foot will have a brightness of 1.076 millilamberts.

865 **Brightness expressed in candles per square centimeter** may be reduced to Lamberts by multiplying by π.

Brightness expressed in candles per square inch may be reduced to foot-candle brightness, by multiplying by the factor $144\,\pi = 452$.

Brightness expressed in candles per square inch may be reduced to lamberts by multiplying by $\pi/6.45 = 0.4868$.

In practice, no surface obeys exactly Lambert's cosine law of emission: hence the brightness of a surface in lamberts is, in general not numerically equal to its specific luminous radiation in lumens per square centimeter.

Defining equations:

$$L = \frac{dF}{dS}$$

Or when uniform

$$L = \frac{F}{S}$$

866 **Coefficient of reflection,** the ratio of the total luminous flux reflected by a surface to the total luminous flux incident upon it. It is a simple numeric. The reflection from a surface may be regular, diffuse or mixed. In perfect regular reflection, all of the flux is reflected from the surface at an angle of reflection equal to the angle of incidence. In perfect diffuse reflection, the flux is reflected from the surface in all directions, in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

867 **Coefficient of regular reflection** is the ratio of the luminous flux reflected regularly to the total incident flux.

868 **Coefficient of diffuse reflection** is the ratio of the luminous flux reflected diffusely to the total incident flux.

Defining equation:

Let m be the coefficient of reflection (regular or diffuse).

Then, for any given portion of the surface,

$$m = \frac{E'}{E}$$

869 **Lamp,** a generic term for an artificial source of light.

870 **Primary luminous standard,** a recognized standard luminous source reproducible from specifications.

871 **Representative luminous standard,** a standard of luminous intensity adopted as the authoritative custodian of the accepted value of the unit.

872 **Reference standard,** a standard calibrated in terms of the unit from either a primary or representative standard and used for the calibration of working standards.

873 **Working standard,** any standardized luminous source for daily use in photometry.

874 **Comparison lamp,** a lamp of constant but not necessarily known candle-power, against which a working standard and test lamps are successively compared in a photometer.

875 **Test lamp,** in a photometer,—a lamp to be tested.

876 **Performance curve,** a curve representing the behavior of a lamp in any particular (candle-power, consumption, etc.) at different periods during its life.

877 **Characteristic curve,** a curve expressing a relation between two variable properties of a luminous source, as candle-power and volts, candle-power and rate of fuel consumption, etc.

878 **Horizontal Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane perpendicular to the axis of the unit, and with the unit at the origin.

879 **Vertical Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane passing through the axis of the unit, and with the unit at the origin. Unless otherwise specified, a vertical distribution curve is assumed to be an *average* vertical distribution curve, such as may in many cases be obtained by rotating the unit about its axis and measuring the average intensities at the different elevations. It is recommended that in vertical distribution curves, angles of elevation shall be counted positively from the nadir as zero, to the zenith as 180 degrees. In the case of incandescent lamps, it is assumed that the vertical distribution curve is taken with the tip downward.

880 **Mean horizontal candle-power** of a lamp,—the average candle-power in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

881 **Mean spherical candle-power** of a lamp,—the average candle-power of a lamp in all directions in space. It is equal to the total luminous flux of the lamp, in lumens, divided by 4π.

882 **Mean hemispherical candle-power** of a lamp (upper or lower),—the average candle-power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp, in that hemisphere, divided by 2π.

883 **Mean zonal candle-power** of a lamp,—the average candle-power of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone, divided by the solid angle of the zone.

884 **Spherical reduction factor** of a lamp,—the ratio of the mean spherical to the mean horizontal candle-power of the lamp.[4]

885 **Photometric Tests** in which the results are stated in candle-power should be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made in the measurement of lamps with reflectors, the results should always be given as "apparent candle-power" at the distance employed, which distance should always be specifically stated.

886 **The output of all illuminants** should be expressed in lumens.

887 **Illuminants should be rated** upon a lumen basis instead of a candle-power basis.

888 **The specific output of electric lamps** should be stated in lumens per watt; and the specific output of illuminants depending upon combustion should be stated in lumens per b.t.u. per hour. The use of the term "efficiency" in this connection should be discouraged.

When auxiliary devices are necessarily employed in circuit with a lamp, the input should be taken to include both that in the lamp and that in the auxiliary devices. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

889 **The Specific Consumption** of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes, watts per mean horizontal candle-power.

890 **Life Tests. Electric Incandescent Lamps** of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life-test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

891 **In Comparing Different Luminous Sources,** not only should their candle-power be compared, but also their relative form, brightness, distribution of illumination and character of light.

892 **Lamp Accessories. A reflector** is an appliance, the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

893 **A Shade is** an appliance, the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions, where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

894 **A Globe is** an enclosing appliance of clear or diffusing materials, the chief use of which is either to protect the lamp, or to diffuse its light.

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4 In case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.

895

TABLE XIX.

Photometric Units and Abbreviations.

Photometric quantity	Name of unit	Abbreviations, Symbols and defining equations
1. Luminous flux	Lumen	$F.\ \Psi$
2. Luminous intensity	Candle	$I = \frac{dF}{d\omega}, \Gamma = \frac{d\Psi}{d\omega}$, cp.
3. Illumination	Phot., foot-candle, lux	$E = \frac{dF}{dS} = \frac{I}{r^2}\cos\theta . \beta$
4. Exposure	Phot-second	$t \quad E$
5. Brightness	Apparent candles per sq. cm. Apparent candles per sq. in.	$b = \frac{dI}{dS \cos\theta}$
	Lambert	$L = \frac{dF}{dS}$
6. Normal brightness	Candles per sq. cm. Candles per sq. in.	$b_0 = \frac{dI}{dS}$
7. Specific luminous radiation	Lumens per sq. cm. Lumens per sq. in.	$E' = \pi b_0 \beta'$
8. Coefficient of re-flection	—	$m = \frac{E'}{E}$

9. Mean spherical candlepower	scp
10. Mean lower hemispherical candlepower	lcp
11. Mean upper hemispherical candlepower	ucp
12. Mean zonal candlepower	zcp

13. 1 lumen is emitted by 0.07958 spherical cp.
14. 1 spherical candlepower emits 12.57 lumens.
15. 1 lux = 1 lumen incident per square meter = 0,0001 phot = 0.1 milliphot.
16. 1 phot = 1 lumen incident per sq. cm. = 10.000 lux = 1000 milliphot.
17. 1 milliphot = 0.001 phot = 0.929 foot-candle.
18. 1 foot-candle = 1 lumen incident per square foot = 1.076 milli-phot = 10.76 lux.
19. 1 lambert = 1 lumen emitted per square centimeter.*
20. 1 millilambert = 0.001 lambert.
21. 1 lumen. emitted. per square foot* = 1.076 millilambert.
22. 1 millilambert = 0.929 lumen, emitted, per square foot*.
23. 1 lambert = 0.3183 candle per sq. cm. = 2.054 candles per sq. in.
24. 1 candle per sq. cm. = 3.1416 lamberts.
25. 1 candle per sq. in. = 0.4868 lamberts = 486.8 millilamberts.

*Perfect diffusion assumed.

896

SYMBOLS.

In view of the fact that the symbols heretofore proposed by this committee conflict in some cases with symbols adopted for electric units by the International Electrotechnical Commission, it is proposed that where the possibility of any confusion exists in the use of electrical and photometric symbols, an alternative system of symbols for photometric quantities should be employed. These should be derived exclusively from the Greek alphabet, for instance:

Luminous intensity........................Γ
Luminous flux........................Ψ
Illumination........................β

STANDARDS FOR TELEPHONY AND TELEGRAPHY

910 After careful consideration, it does not seem that the time is yet ripe for a formal standardization of terms and definitions used in telephony and telegraphy. Many of the terms commonly employed are used in more than a single way, and conversely, many pieces of apparatus and many constants which are essentially identical from a physical standpoint have been and are known by more than one designation.

911 **Damping of a Circuit.** The damping, at a given point, in a circuit from which the source of energy has been withdrawn, is the progressive diminution in the effective value of electromotive force and current at that point resulting from the withdrawal of electrical energy.

912 **Damping Constant.** The damping constant of a circuit depends upon the ratio of the dissipative to the reactive component of its impedance or admittance.

Applied to the admittance of a condenser or other simple circuit having capacity reactance, the damping constant for a harmonic electromotive force of given frequency is the ratio of the conductance of the condenser or simple circuit at that frequency, to twice the capacity of the condenser at the same frequency.

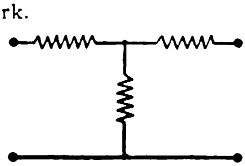
Applied to the reactance of a coil or other simple circuit having inductive reactance, the damping constant for a harmonic current of given frequency is the ratio of the resistance of the coil or circuit at that frequency, to twice the inductance at the same frequency.

913 **Equivalent Circuit.** An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network at the same frequency and under steady-state conditions.

NOTE: As ordinarily considered, the simple networks as defined, are the electrical equivalents of complex networks only with respect to definite pairs of terminals, and only as to sending-end impedances, and total attenuation. A further requirement is that the only connections between the pairs of terminals are those through the network itself.

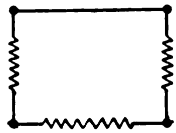
914 **"T" Equivalent Circuit.** A "T" equivalent circuit is a triple-star or "Y" connection of three impedances externally equivalent to a complex network.

Symbol:



915 **"U" Equivalent Circuit.** A "U" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "Π" equivalent circuit.

Symbol:



IMPEDANCE

916 **Mutual Impedance.** The mutual impedance, for alternating currents, between a pair of terminals and a second pair of terminals of a network, under any given condition, is the negative vector ratio of the electromotive force produced between either pair of terminals on open circuit, to the current flowing between the other pair of terminals.

917 **Self Impedance.** The self impedance between a pair of terminals of a network, under any given condition, is the vector ratio of the electromotive force applied across the terminals to the current produced between them.

LINE CHARACTERISTICS

918 **Characteristic Impedance.** The characteristic impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current upon a line of infinite length and uniform structure, or of periodic recurrent structure.

NOTE: In telephone practice, the terms (1) line impedance, (2) surge impedance, (3) iterative impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final sending-end impedance, (7) natural impedance and (8) free impedance, have apparently been more or less indefinitely and indiscriminately used as synonyms with what is here defined as "characteristic impedance."

919 **Sending-End Impedance.** The sending-end impedance of a line is the vector ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

NOTE: See note under "Characteristic Impedance." In case the line is of infinite length of uniform structure or of periodic recurrent structure, the sending-end impedance and the characteristic impedance are the same.

920 **Propagation Constant.** The propagation constant per unit length of a uniform line, or per section of a line of periodic recurrent structure, is the natural logarithm of the vector ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite length. The ratio is determined by dividing the value of the current at the point nearer the transmitting end by the value of the current at the point more remote.

921 **Attenuation Constant.** The attenuation constant is the real part of the propagation constant.

922 **Wave-Length Constant.** The wave-length constant is the imaginary part of the propagation constant.

LINE CIRCUITS

930 **Ground-Return Circuit.** A ground-return circuit is a circuit consisting of one or more metallic conductors in parallel, with the circuit completed through the earth.

931 **Metallic Circuit.** A metallic circuit is a circuit of which the earth forms no part.

932 **Two-Wire Circuit.** A two-wire circuit is a metallic circuit formed by two paralleling conductors insulated from each other.

933 **Superposed Circuit.** A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

934 **Phantom Circuit.** A phantom circuit is a superposed circuit, each side of which consists of the two conductors of a two-wire circuit in parallel.

935 **Side Circuit.** A side circuit is a two-wire circuit forming one side of a phantom circuit.

936 **Non-Phantomed Circuit.** A non-phantomed circuit is a two-wire circuit, which is not arranged for use as the side of a phantom circuit.

937 **Simplexed Circuit.** A simplexed circuit is a two-wire telephone circuit, arranged for the super-position of a single ground-return signalling circuit-operating over the wires in parallel.

NOTE: In view of the use of the term "Simplex Operation" in telegraph practice, it is felt that the designation "Simplexed Circuit" as applied to the arrangement described is not a happy one.

938 **Composited Circuit.** A composited circuit is a two-wire telephone circuit, arranged for the superposition on each of its component metallic conductors, of a single independent ground-return signalling circuit.

939 **Quadded or Phantomed Cable.** A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

NOTE: The type of cable here defined has frequently been designated as "Duplex Cable"—a term which is objectionable both on account of its lack of description and its widely different use in telegraph practice.

LOADING

950 **Loaded Line.** A loaded line is one in which the normal inductance of the circuit has been altered for the purpose of increasing its transmission efficiency for one or more frequencies.

951 **Series Loaded Line.** A series loaded line is one in which the normal inductance has been altered by inductance serially applied.

952 **Shunt Loaded Line.** A shunt loaded line is one in which the normal inductance of the circuit has been altered by inductance applied in shunt across the circuit.

953 **Continuous Loading.** A continuous loading is a series loading in which the added inductance is uniformly distributed along the conductors.

954 **Coil Loading.** A coil loading is one in which the normal inductance is altered by the insertion of lumped inductance in the circuit at intervals. This lumped inductance may be applied either in series or in shunt.

NOTE: As commonly understood, coil loading is a series loading, in which the lumped inductance is applied at uniformly spaced recurring intervals

955 **Microphone.** A contact device designed to have its electrical resistance directly and materially altered by slight differences in mechanical pressure.

956 **Relay.** A relay is a device by means of which contacts in one circuit are operated under the control of electrical energy in the same or other circuits.

957 **Resonance.** Resonance of a harmonic alternating current of given frequency, in a simple series circuit, containing resistance, inductance and capacity, is the condition in which the positive reactance of the inductance is numerically equal to the negative reactance of the capacity. Under these conditions, the current flow in the circuit with a given electromotive force is a maximum.

958 **Retardation Coil.** A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

NOTE: In telephone and telegraph usage, the terms "impedance coil," "inductance coil," choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

959 **Skin Effect.** Skin effect is the phenomenon of the non-uniform distribution of current throughout the cross-section of a linear conductor, occasioned by variations in the intensity of the magnetic field due to the current in the conductor.

960 **Telephone Receiver.** A telephone receiver is an electrically operated device, designed to produce sound waves or vibrations which correspond in form to the electromagnetic waves or vibrations actuating it.

961 **Telephone Transmitter.** A telephone transmitter is a sound-wave or vibration-operated device designed to produce electromagnetic waves or vibrations which correspond in form to the sound waves or vibrations actuating it.

962 **The Coefficient of Coupling of a Transformer.** The coefficient of coupling of a transformer at a given frequency, is the vector ratio of the mutual impedance between the primary and secondary of the transformer, to the square root of the product of the self-impedances of the primary and of the secondary.

963 **Repeating Coil.** A term used in telephone practice meaning the same as transformer, and ordinarily a transformer of unity ratio.

APPENDIX I.

STANDARDS FOR RADIO COMMUNICATION

The following Sections **1000** to **1033** have been prepared by the Standardization Committee of the Institute of Radio Engineers, and are here included by permission as an Appendix, until further revised.

1000 Acoustic Resonance Device. One which utilizes, in its operation, resonance to the audio frequency of the received impulses.

1001 Antenna. A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

1002 Atmospheric Absorption. That portion of the total loss of radiated energy due to atmospheric conductivity.

1003 Audio Frequencies. The normally audible frequencies lying below 20,000 cycles per second (see also radio frequencies).

1004 Capacitive Coupler. An apparatus which, by electric fields, joins portions of two radio frequency circuits and is used to transfer electrical energy between these circuits through the action of electric forces.

1005 Coefficient of Coupling (Inductive). The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

1006 Direct Coupler. An apparatus which magnetically joins two circuits having a common conductive portion and which is used to transfer electrical energy between these circuits.

1007 Counterpoise. A system of electrical conductors insulated from ground forming one plate of a condenser, the other plate of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

1008 A Damped Alternating Current is a current which alternates regularly in direction and whose amplitude progressively diminishes.

1009 The Damping Factor of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let I_0 = initial amplitude

I_t = amplitude at the time t

ϵ = base of Napierian logarithms

a = damping factor

Then: $I_t = I_0 \, \epsilon^{-at}$

1010 Detector. That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio frequency energy into a form suitable for operation of

the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

1011 **Electromagnetic Wave.** A progressive disturbance characterized by the existence on the wave front of electric and magnetic forces acting in directions which are perpendicular to each other and to the direction of propagation of the wave.

1012 **Forced Alternating Current.** A current produced in any circuit by the application of an alternating electromotive force.

1013 **Free Alternating Current.** A current produced by means of an electromagnetic disturbance in a circuit, having capacity, inductance, and *less* than the critical resistance.

1014 **Critical Resistance of a Circuit** determines the limit between the oscillatory and aperiodic discharge of that circuit. (The discharge is aperiodic if the circuit resistance is greater than the critical value and is alternating when the resistance is less than the critical value). In a circuit without dielectric or magnetic hysteresis, the critical resistance equals $2\sqrt{\frac{L}{C}}$, where L and C are the effective inductance and capacity of the circuit.

1015 **Group Frequency.** The number per second of periodic changes in amplitude or frequency of an alternating current.

NOTE 1. Where there is more than one periodic recurrent change of amplitude or frequency, there is more than one group frequency present.

NOTE 2. The term "group frequency" replaces the term "spark frequency."

1016 **Inductive Coupler.** An apparatus which, by magnetic forces, joins portions of two radio frequency circuits and is used to transfer electrical energy between these circuits, through the action of magnetic forces.

1017 **Linear Decrement of a Linearly Damped Alternating Current** is the difference of successive current amplitudes in the same direction, divided by the larger of these amplitudes.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction, of a linearly-damped alternating current.

Then: The linear decrement, $b = \frac{I_n - I_{n+1}}{I_n}$

Also: $I_t = I_0 \, (1 - bft)$

Where: I_0 = initial current amplitude

I_t = current amplitude at time t

f = frequency of alternating current

1018 **Logarithmic Decrement** of an exponentially damped alternating current is the logarithm of the ratio of successive current amplitudes in the same direction.

NOTE: Logarithmic decrements are standard for a complete period or cycle.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction.

d = logarithmic decrement

Then: $$d = \log_\epsilon \frac{I_n}{I_{n+1}}$$

1019 Radio Frequencies. Those above 20,000 cycles per second (see also Audio Frequencies).

NOTE: It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience.

1020 Resonance to an Exciting Alternating Current of a given frequency in an oscillating circuit is that condition in which the resulting effective current (or voltage) in that circuit is a maximum.

If neither the free nor the forced alternating currents of the driven circuit are highly damped, then resonance is obtained when the frequency of the free alternating current is approximately equal to the frequency of the forced alternating current.

That is, $$\omega = \frac{1}{\sqrt{LC}} = \omega_1$$

Where: ω = $2\pi\times$ the frequency of the free alternating current in the circuit.

L = the effective inductance of the circuit.

C = the effective capacity of the circuit.

ω_1 = angular velocity of the forced alternating current.

This is equivalent to the condition $\omega L = \frac{1}{\omega C}$ *i.e.*, the inductive reactance at that frequency is numerically equal to the capacitive reactance, or that the total reactance $\left(\omega L - \frac{1}{\omega C}\right)$ is equal to 0.

1021 A Resonance Curve gives the power, current, or voltage at various frequencies of excitation, as a function of those frequencies. or of the corresponding wave lengths.

1022 A Wave-Length Resonance Curve is one wherein the abscissas are ratios of specified wave lengths to the resonant wave length, and the ordinates are ratios of the energy (or square of the current) at corresponding specified wave lengths to the energy (or square of the current) at the resonant wave length. It is advantageous to have the scales of ordinates and abscissas equal.

1023 A Frequency Resonance Curve. One wherein the abscissas are ratios of specified frequencies to the resonant frequency, and the ordinates are ratios of the energy (or square of the current) at corresponding specified frequencies to the energy (or square of the current) at the resonant frequency. The scales of ordinates and abscissas are equal.

1024 A Standard Resonance Curve, unless otherwise specified, is assumed to be a wave-length resonance curve.

1025 Selecting. The process of adjusting an element driven by a plurality of simultaneous impulses, until the ratio of desired response to undesired response is a maximum.

1026 Sustained Radiation consists of electromagnetic waves of constant amplitude (such as are emitted from an antenna in which a forced alternating current flows.)

1027 Tuning. The process of securing the maximum indications by adjusting the time period of a driven element. (In transmitter or receiver.)

1028 A Wave-Length Meter commonly called a **Wave-Meter,** is a radio frequency measuring instrument, calibrated to read wave lengths.

1029 Rating. 1. All radio transmitting sets shall be rated in actual power output measured in the antenna.

NOTE: The group or audio frequency of the note of the station should be stated as well, (except for sustained wave sets, where that characteristic should be mentioned).

2. The over-all efficiency of a radio transmitting station shall be the ratio of the actual power output as measured in the antenna to the power input supplied to the first piece of electrical machinery which is definitely a part of the radio equipment.

1030 Decremeter. An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

1031 Attenuation, Radio. The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

1032 Attenuation Coefficient (Radio). The coefficient, which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

1033 Coupler. An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

APPENDIX II.

ADDITIONAL STANDARDS FOR RAILWAY MOTORS

1100 In comparing projected motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

TABLE XX

Approximate Losses in D.C. Railway Motors.

Input in per cent of that at nominal rating	Losses as per cent of input
100 or over	5.0
75	5.0
60	5.3
50	6.5
40	8.8
30	13.3
25	17.0

1101 The core loss of railway motors is sometimes determined by separately exciting the field, and driving the armature of the motor to be tested, by a separate motor having known losses and noting the differences in losses between driving the motor light at various speeds and driving it with various field excitations.

1102 **Selection of Motor For Specified Service**

The following information relative to the service to be performed, is required, in order that an appropriate motor may be selected.

(a) Weight of total number of cars in train (in tons of 2000 lb.) exclusive of electrical equipment and load.

(b) Average weight of load and durations of same, and maximum weight of load and durations of same.

(c) Number of motor cars or locomotives in train, and number of trailer cars in train.

(d) Diameter of driving wheels.

(e) Weight on driving wheels, exclusive of electrical equipment.

(f) Number of motors per motor car.

(g) Voltage at train with power on the motors—average, maximum and minimum.

(h) Rate of acceleration in mi. per. hr. per second.
(i) Rate of braking (retardation in m. per hr. per second).
(j) Speed limitations, if any (including slowdowns).
(k) Distances between stations.
(l) Duration of station stops.
(m) Schedule speed including station stops in m.p.h.
(n) Train resistance in pounds per ton of 2000 pounds at stated speeds.
(o) Moment of inertia of revolving parts, exclusive of electrical equipment.
(p) Profile and alignment of track.
(q) Distance coasted as a per cent of the distance between station stops.
(r) Time of layover at end of run, if any.

1103 **Stand-Test Method of Comparing Motor Capacity with Service Requirements:** When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature rise.

1104 The essential motor losses affecting temperatures in service are those in the motor windings, core and commutator. The mean service conditions may be expressed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average in service.

A stand test with the current and voltage which will give losses equal to those in service, will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor (**§164**), well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 per cent (depending upon the character of the service) of the temperature rise obtained on a stand test with the motor completely enclosed and with the same losses. With a ventilated motor (**§165 and §167**), the temperature rise in service will be 90 to 100 per cent of the temperature rise obtained on a stand test with the same losses.

1105 In making a stand test to determine the temperature rise in a specific service, it is essential in the case of a self-ventilated motor (**§ 167**), to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

1106 **Calculation for Comparing Motor Capacity with Service Requirements.** The heating of a motor should be determined, wherever possible, by testing it in service, or with an equivalent duty cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilized as follows to determine its temperature rise.

1107 The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with

the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

1108 (a) Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty cycle which the motor is to perform, and calculate from these the root-mean-square current and the equivalent voltage which, with this r.m.s. current, will produce the average core loss.

1109 (b) If the calculated r.m.s. service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty cycle contemplated.

1110 (c) If the calculated r.m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service. In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to calculate the temperature rise due to the r.m.s. service current, and equivalent voltage.

Let t = temperature rise, $p_0 = I^2R$ loss, kw., p_c = core loss, kw. } with r.m.s. service current, and equivalent service voltage.

T = temperature rise, $P_0 = I^2R$ loss, kw., P_c = core loss, kw. } with continuous load current corresponding to the equivalent service voltage.

Then

$$t = T\frac{p_0 + p_c}{P_0 + P_c}, \text{ approximately.}$$

1111 (d) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one hour test starting at ambient temperature.

1112 (e) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r.m.s. service current and equivalent voltage. The excess loss, divided by the co-efficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

1113 (f) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty cycle.

APPENDIX III.

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